

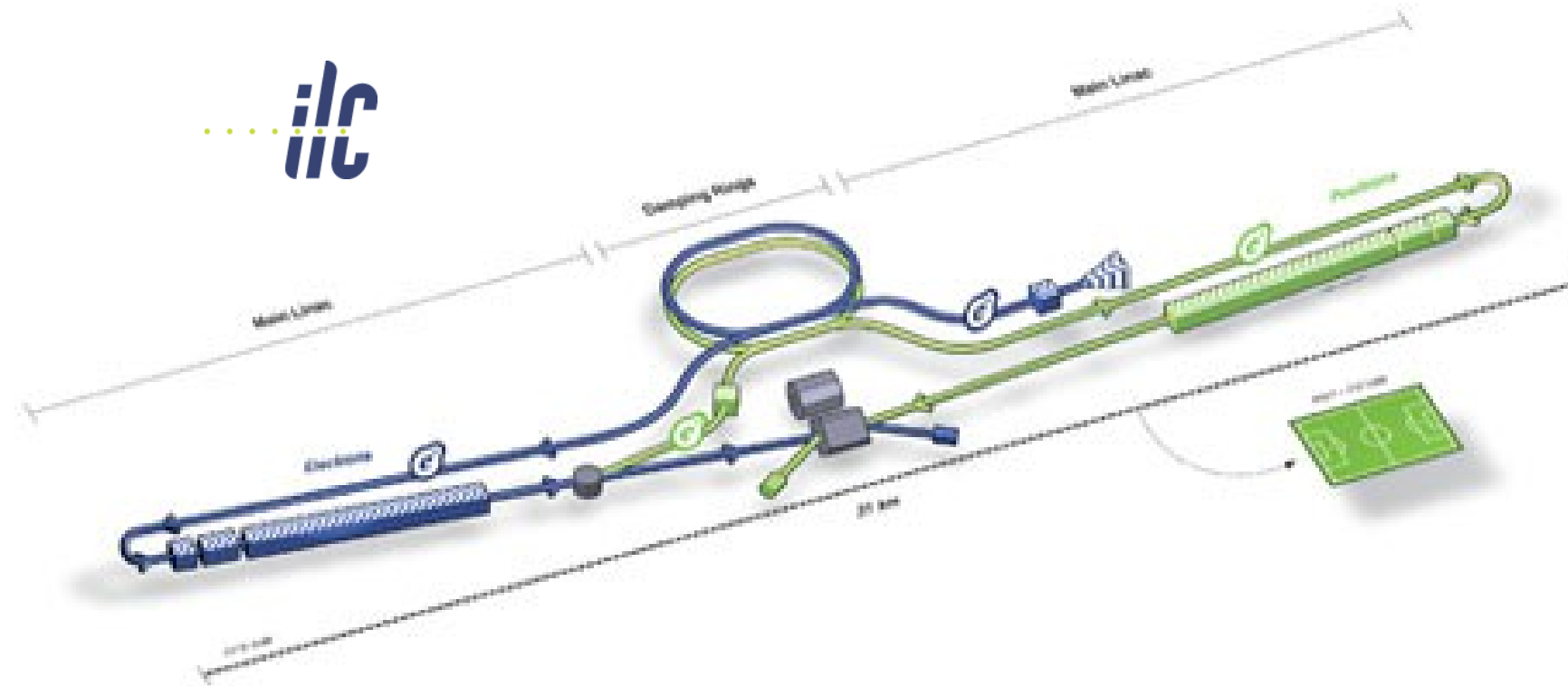
# Top and Heavy quark studies at linear colliders

Roman Pöschl



Snowmass EF Workshop August/September 2021

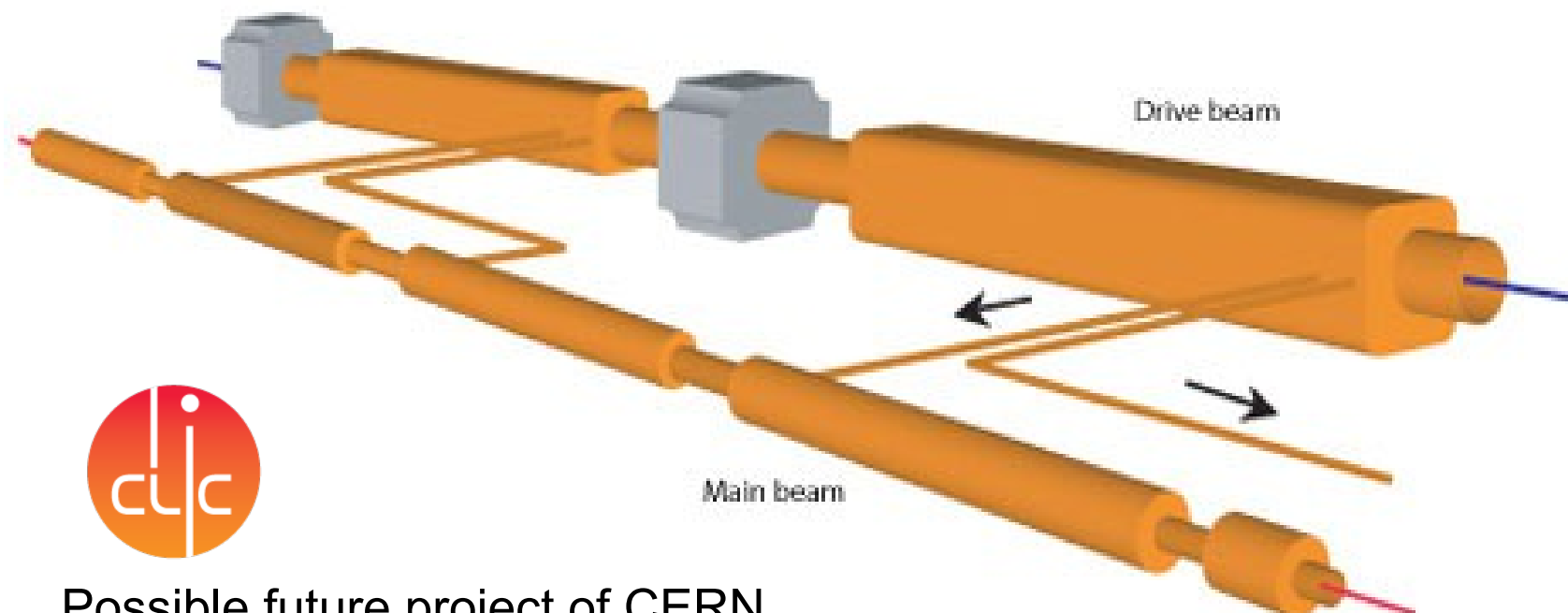
# Linear Electron positron colliders



**Energy: 0.1 - 1 TeV**  
**Electron (and positron)**  
**polarisation**  
**TDR in 2013**  
**+ DBD for detectors**  
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km

Under discussion in Japanese Government and international community



**Energy: 0.4 - 3 TeV**

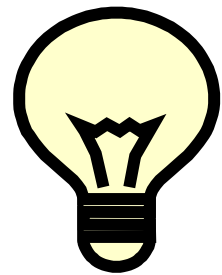
**CDR in 2012**  
**Update 2016**

Footprint 48km

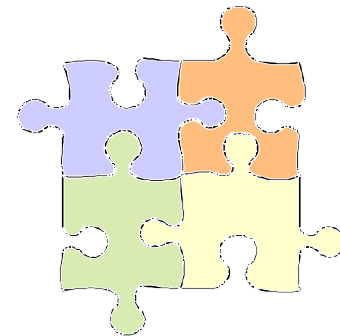
Initial Energy 380 GeV



Possible future project of CERN

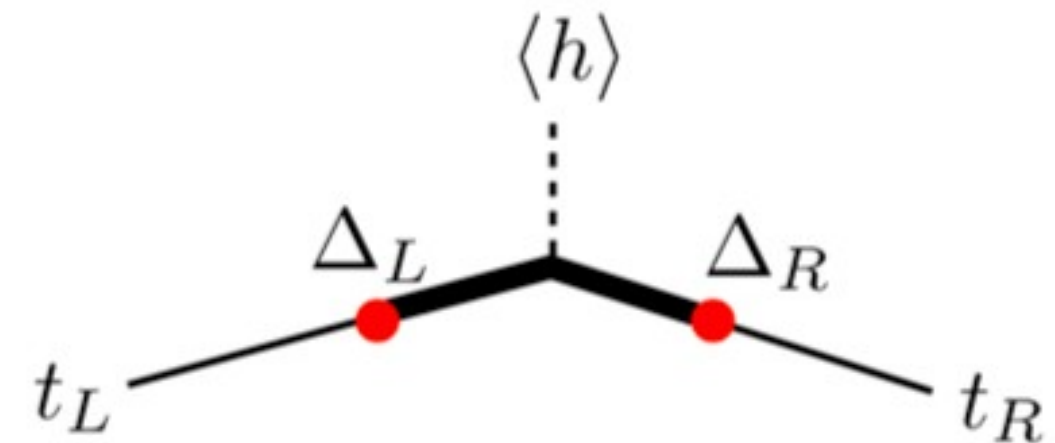
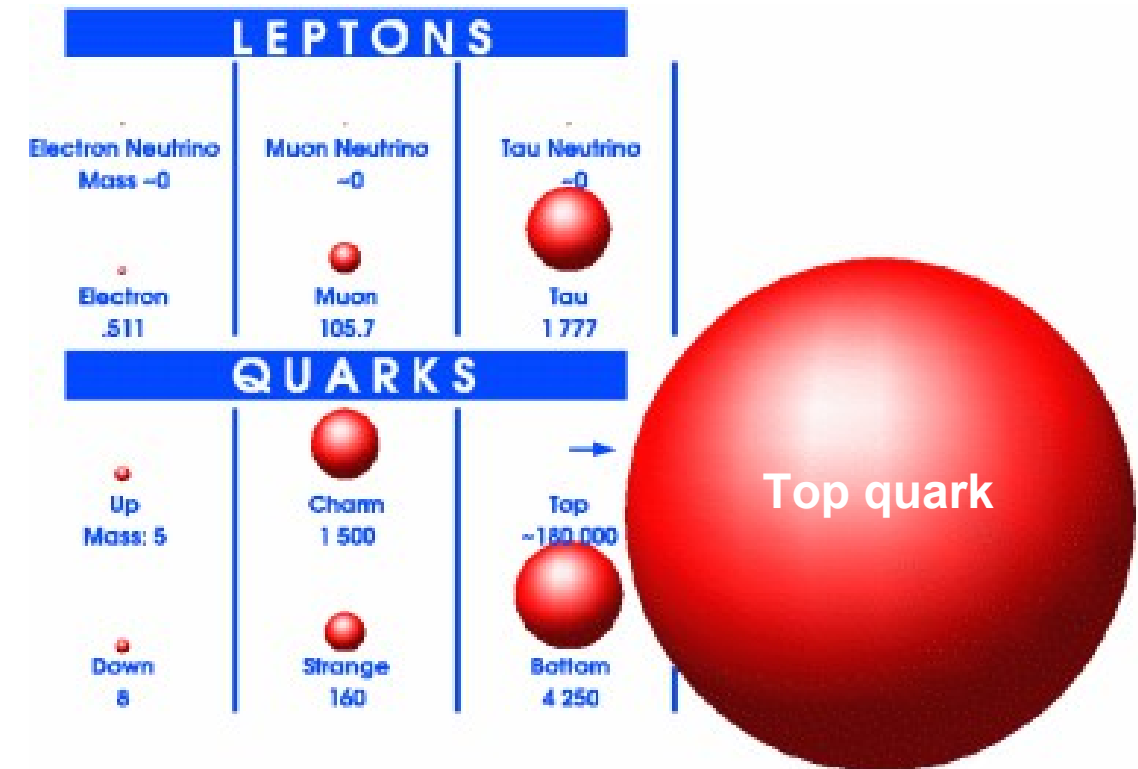


Elementary Scalar?



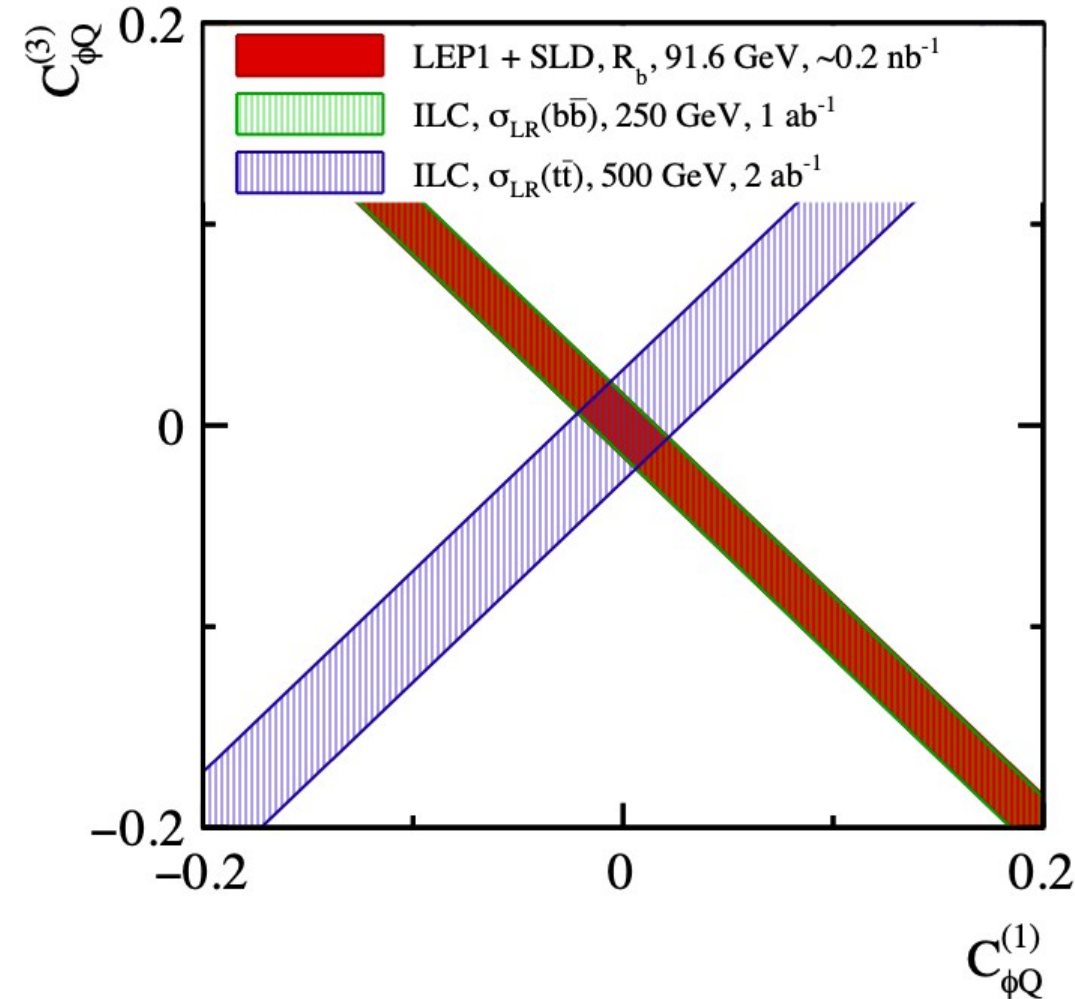
Composite object?

- Higgs and top quark are intimately coupled!  
Top Yukawa coupling  $O(1)$  !  
=> Top mass important SM Parameter
- New physics by compositeness?  
Higgs and top composite objects?
- $e^+e^-$  collider perfectly suited to decipher both particles

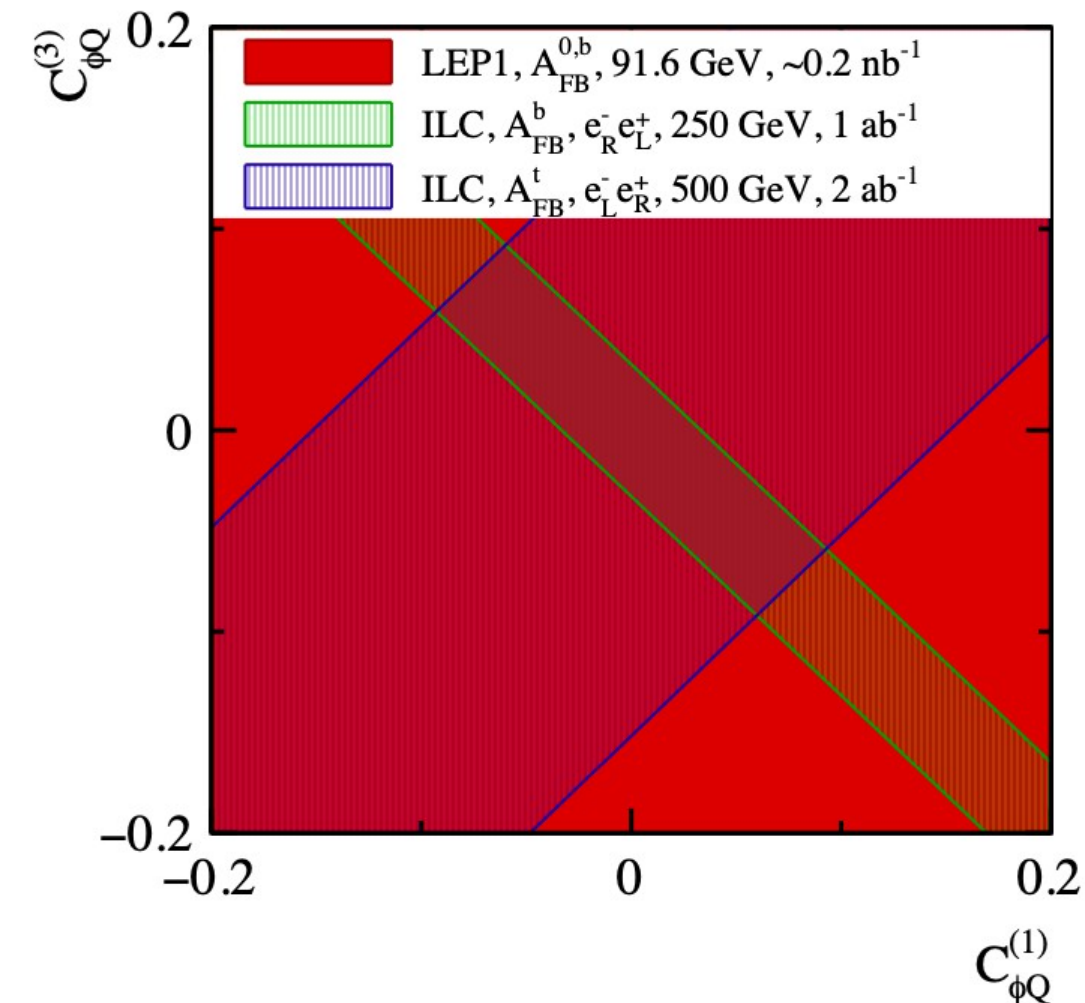


Courtesy of S. Rychkov

From cross section

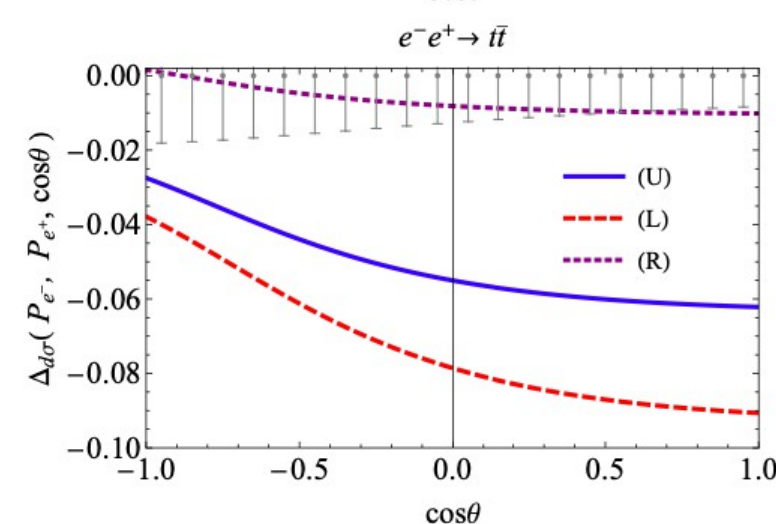
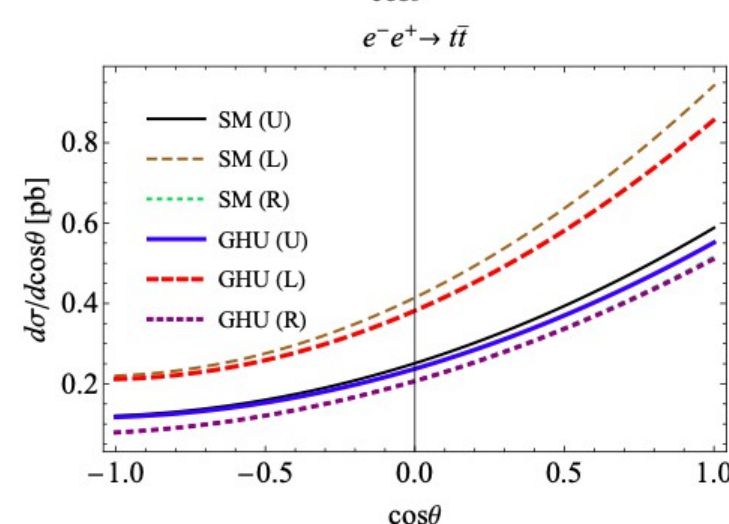
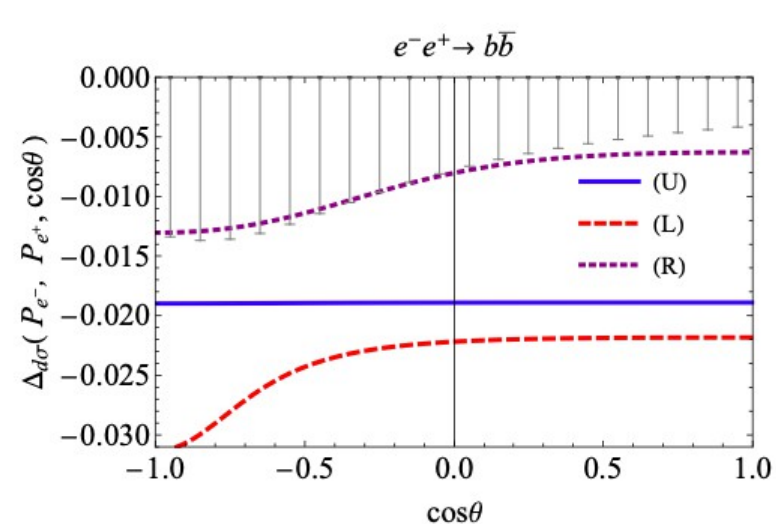
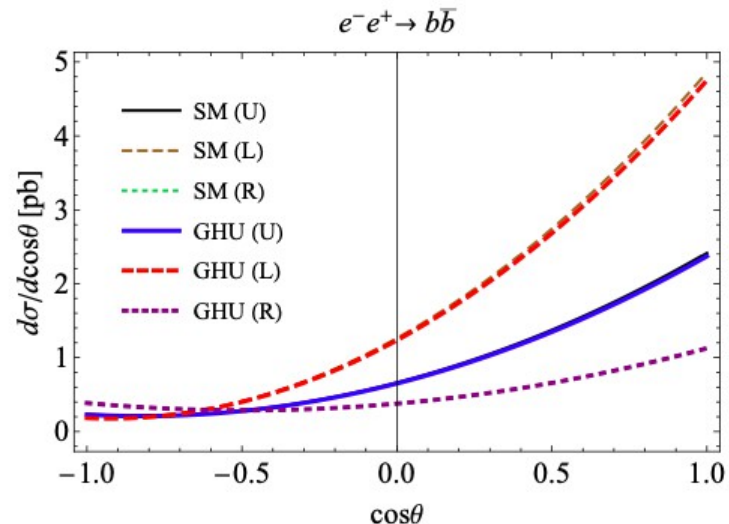
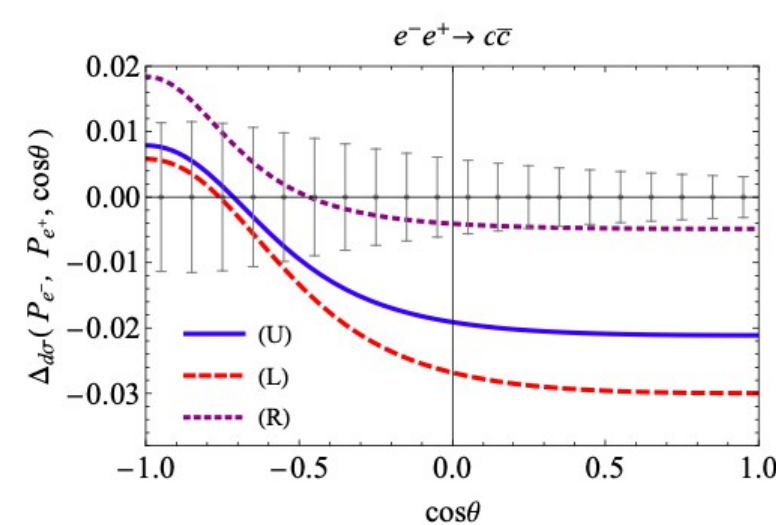
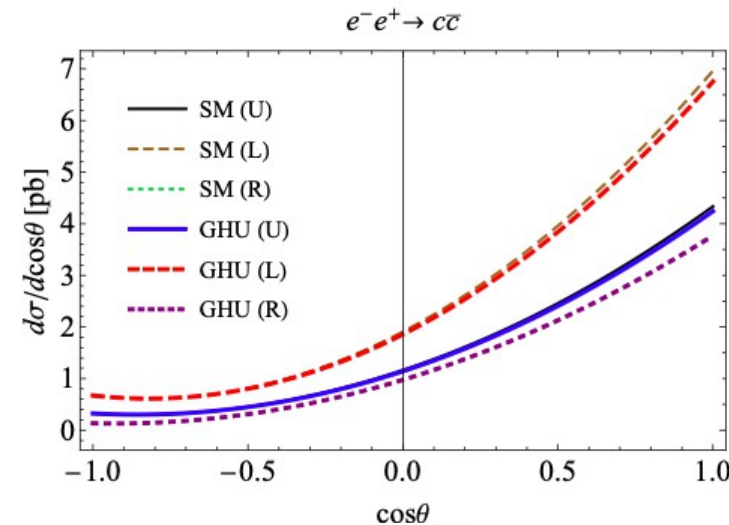


From forward-backward asymmetry



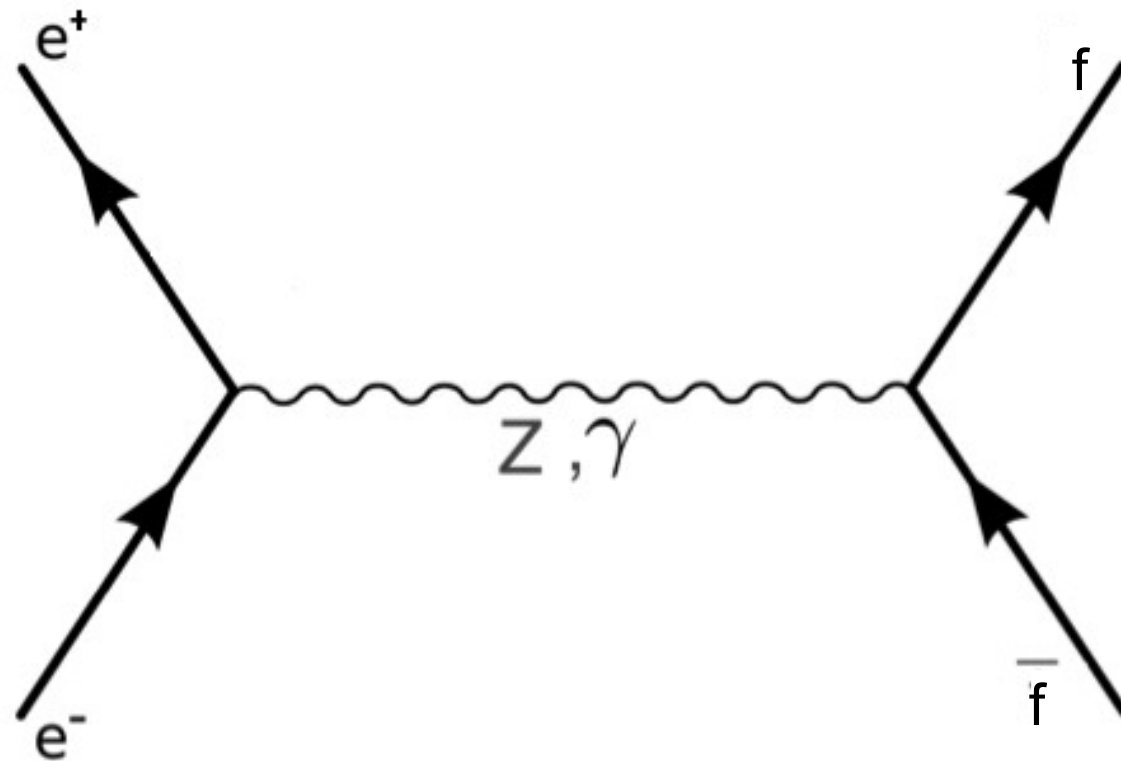
- Measurement of bottom and top observables delivers complementary information for EFT operators
- **ILC@250** GeV comparable to LEP in terms of cross section => Constrain on  $g_{Lb}$
- **ILC@250** GeV drastically better than LEP in terms of AFB => Constrain on  $g_{Rb}$
- How would the picture look with GigaZ precisions?





arxiv:2006.02157

- Model parameter is Hosotani angle  $\theta_H$  yielding the Higgs-Potential as consequence of Aharonov-Bohm Phase in 5<sup>th</sup> dimension
- Model defined in Randall-Sundrum warped extra dimensions
  - KK excitations of gauge bosons and new bosons modify fermion couplings
- Predictions for ILC
  - $m_{KK} = 13$  TeV and  $\theta_H = 0.1$
- Deviations from SM of the order of a few %
  - Effects measurable already at 250 GeV
  - Effects amplified by beam polarisations
  - Effects for tt, bb and cc (and other light fermions)
- One concrete example for importance to measure full pattern of fermion couplings
- Full pattern only available with beam polarisation



Differential cross sections for (relativistic) di-fermion production\*:

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \rightarrow f \bar{f}) = \Sigma_{LL}(1 + \cos\theta)^2 + \Sigma_{LR}(1 - \cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \rightarrow f \bar{f}) = \Sigma_{RL}(1 + \cos\theta)^2 + \Sigma_{RR}(1 - \cos\theta)^2$$

\*add term  $\sim \sin^2\theta$  in case of non-relativistic fermions e.g. top close to threshold

$\Sigma_{IJ}$  are helicity amplitudes that contain couplings  $g_L, g_R$  (or  $F_V, F_A$ )

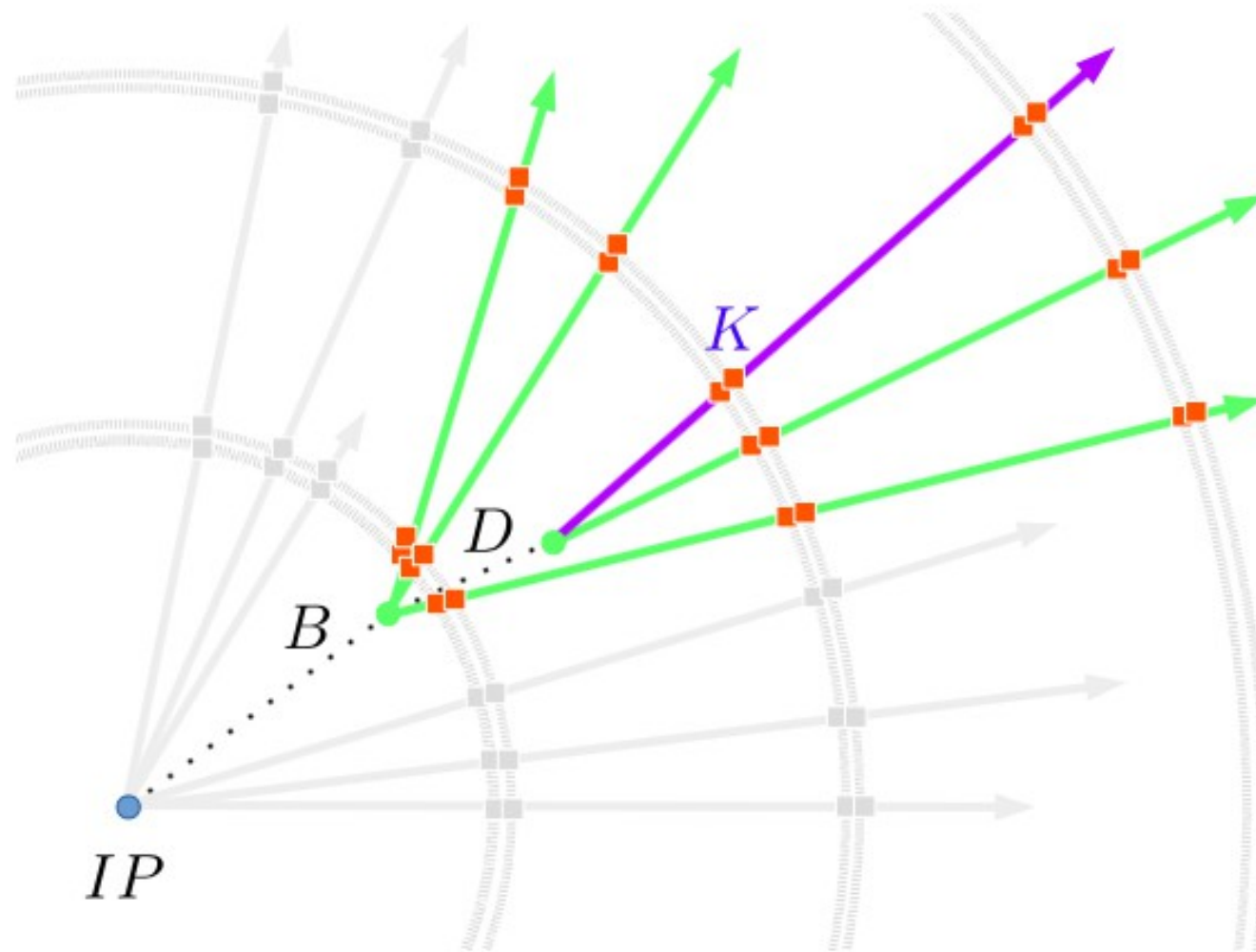
$\Sigma_{IJ} \neq \Sigma_{I'J}' \Rightarrow$  (characteristic) asymmetries for each fermion

Forward-backward in angle, general left-right in cross section

**All four helicity amplitudes for all fermions only available with polarised beams**

**So far tt, bb and cc pair production**

**New ss production**

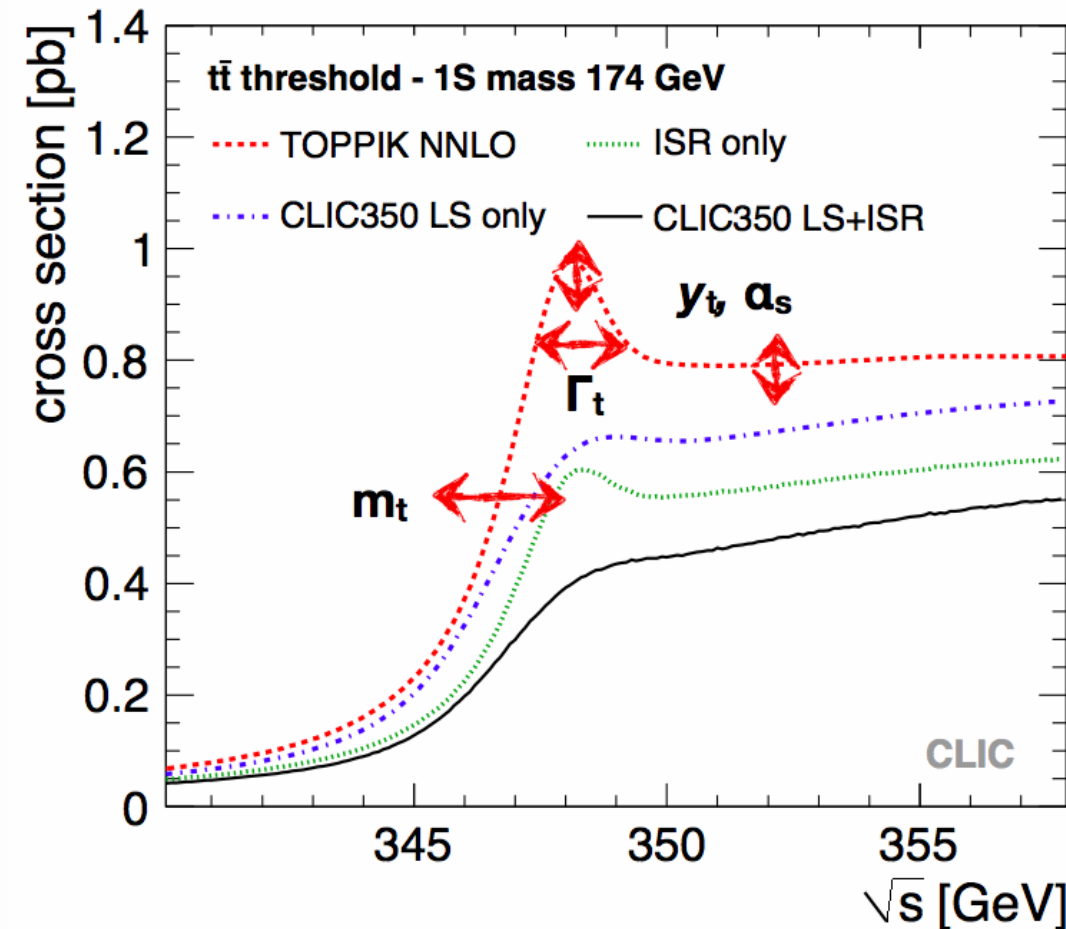
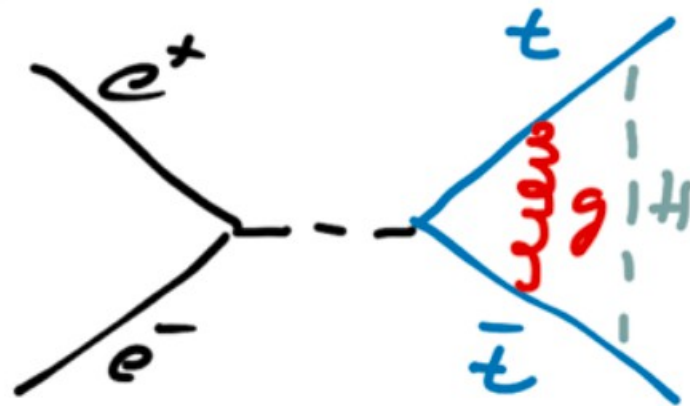


- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for  $ee \rightarrow bb, cc, ss, \dots$
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by  $dE/dx$  (and more)
- Future detectors can base the entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and Semi-leptonic events

Small size of  $t\bar{t}$  “bound state” at threshold ideal premise for precision physics

Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant



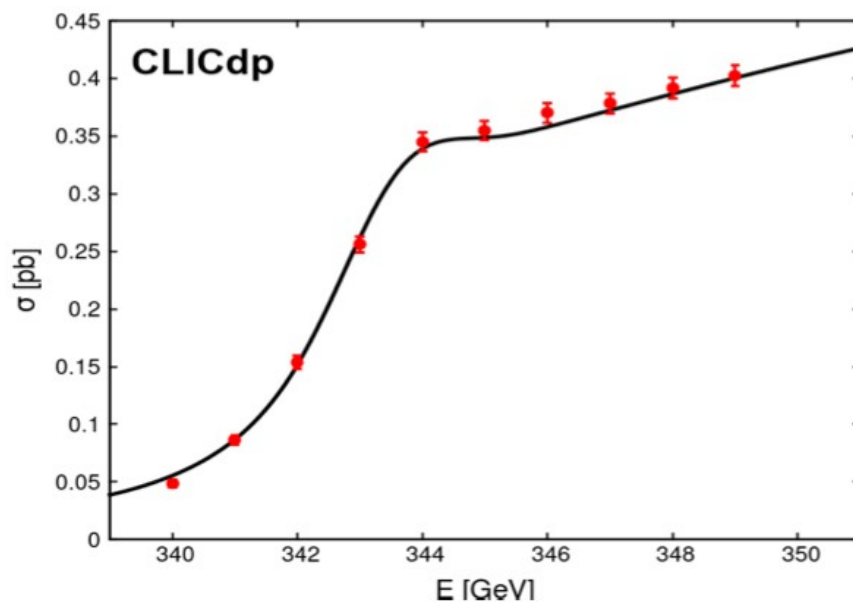
- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external  $\alpha_s$  helps



Optimisation of threshold scan using “Non dominated sorting **genetic algorithm**”

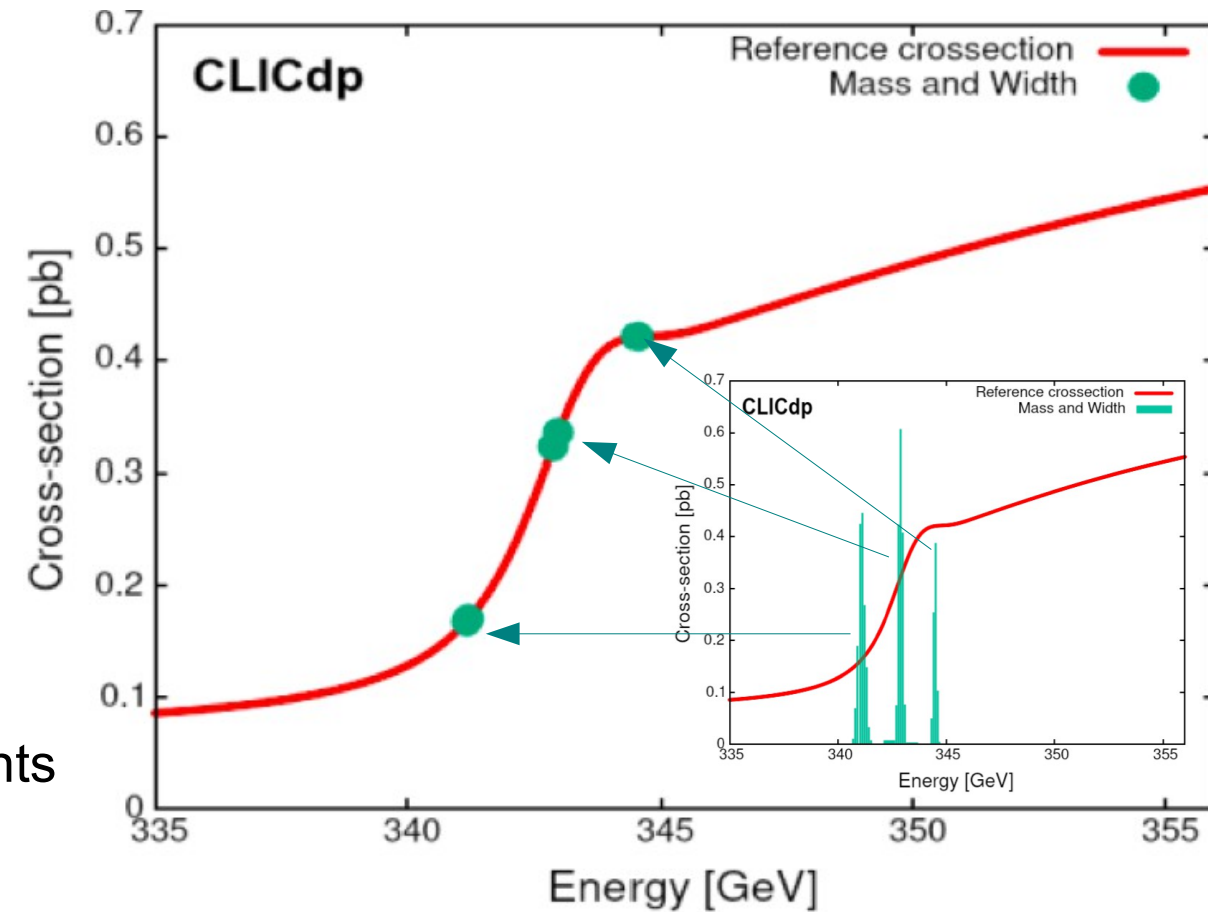
*arxiv: 2103.00522*

Standard scan scenario

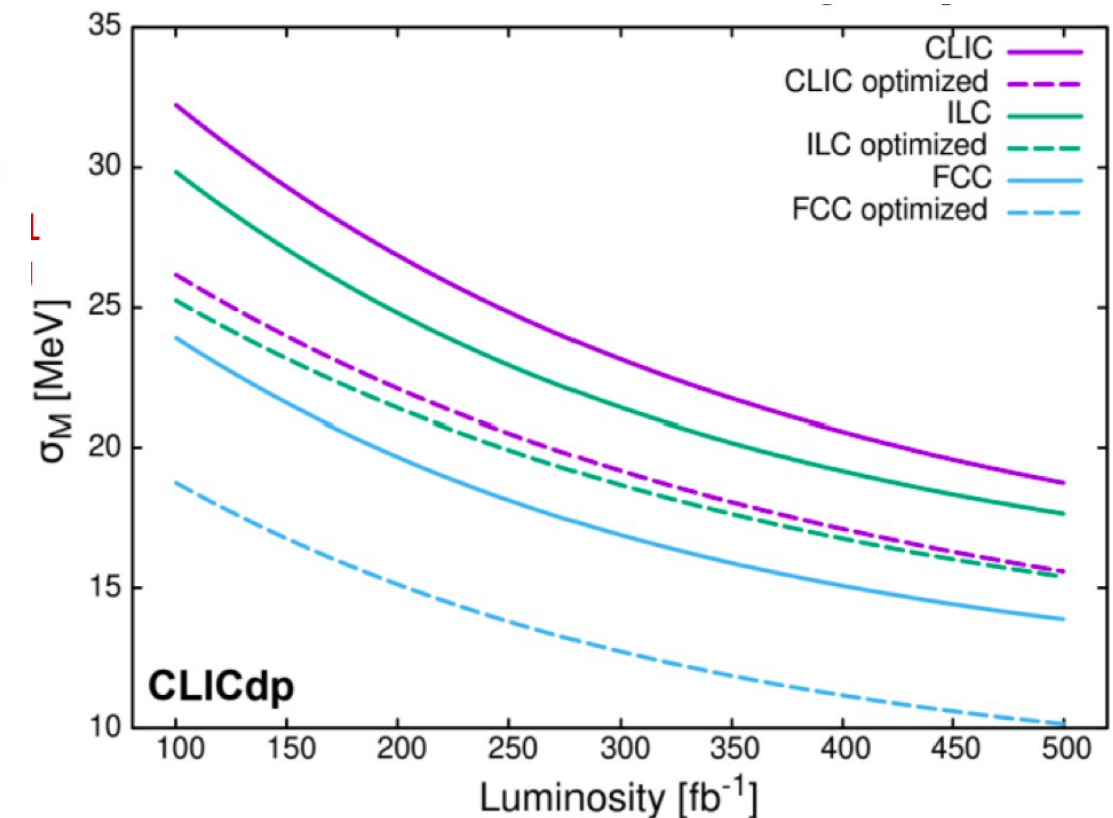


100 fb<sup>-1</sup> for 10 equally distributed points

Optimised scenario for mass a width

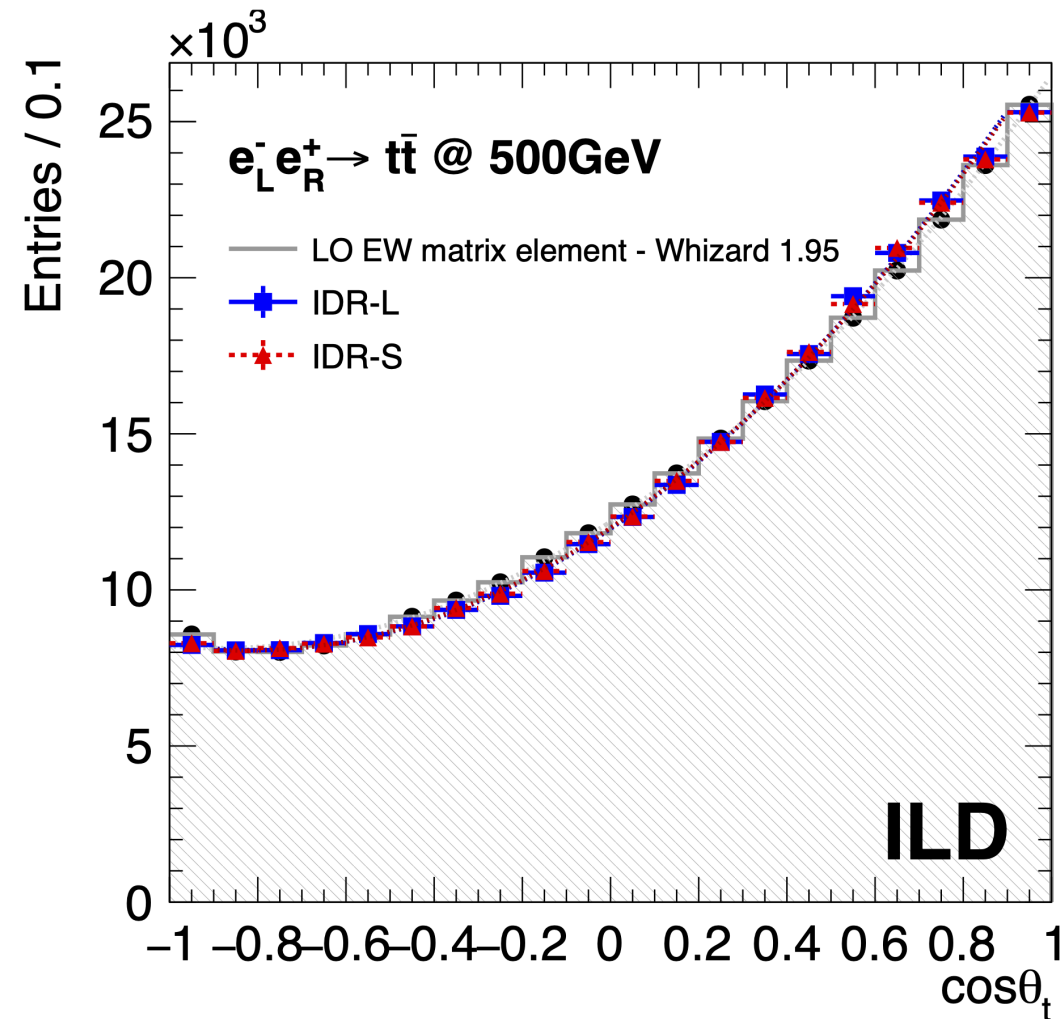


Precision on top mass ...

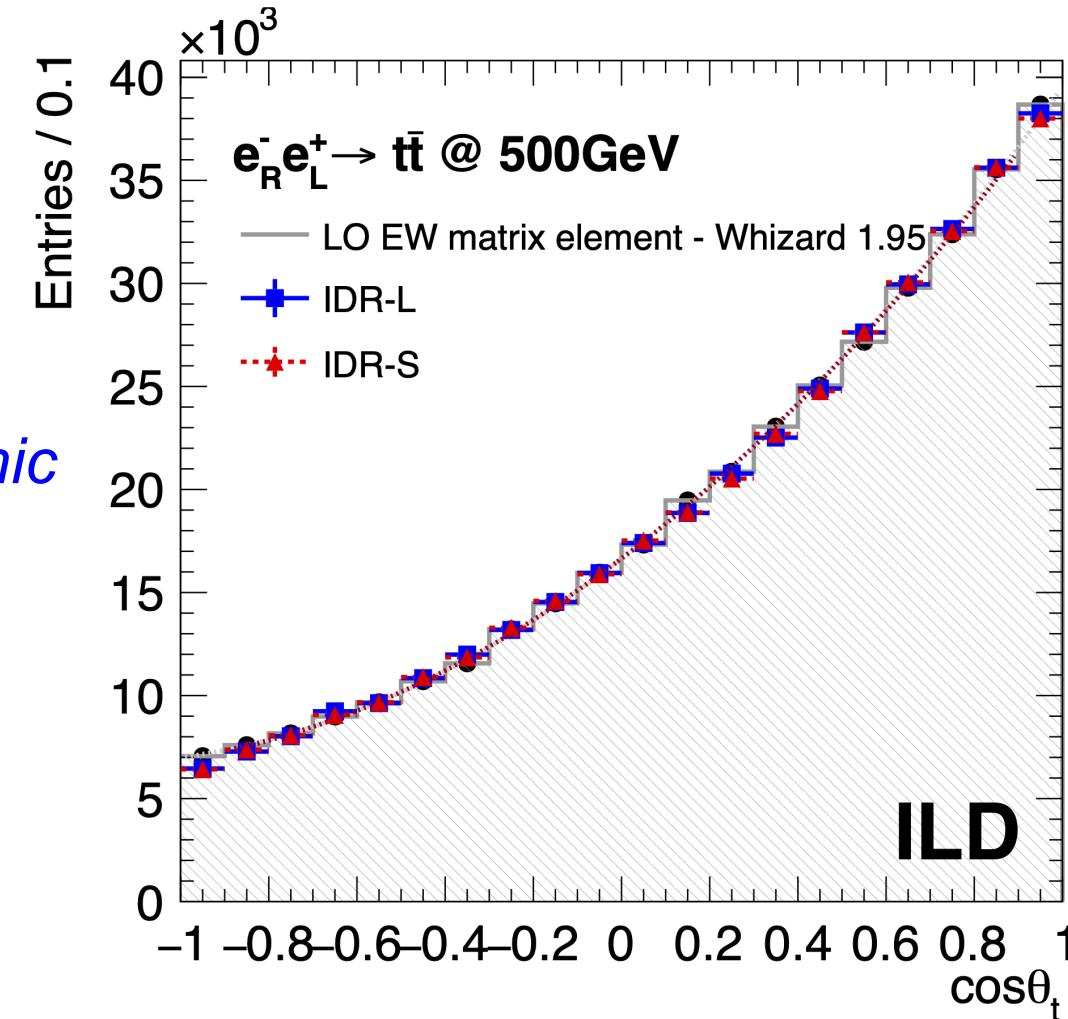


... taking luminosity spectrum into account

- Optimisation of threshold scan yield 25% statistical precision of top mass compared with scan using equally distributed scan points
  - Choice of measurement points with optimal sensitivity to desired quantity
- For breakdown of systematic errors see backup



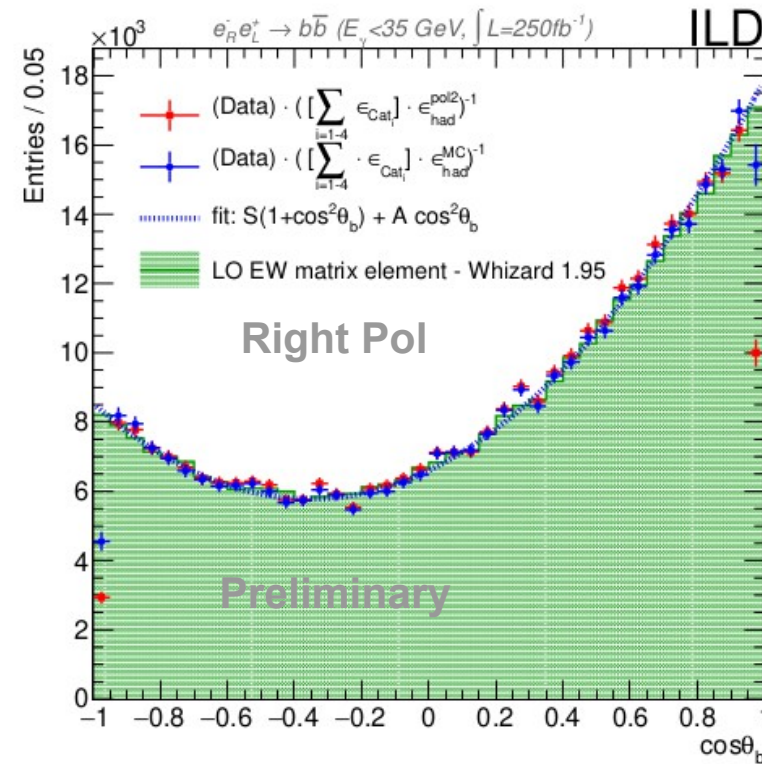
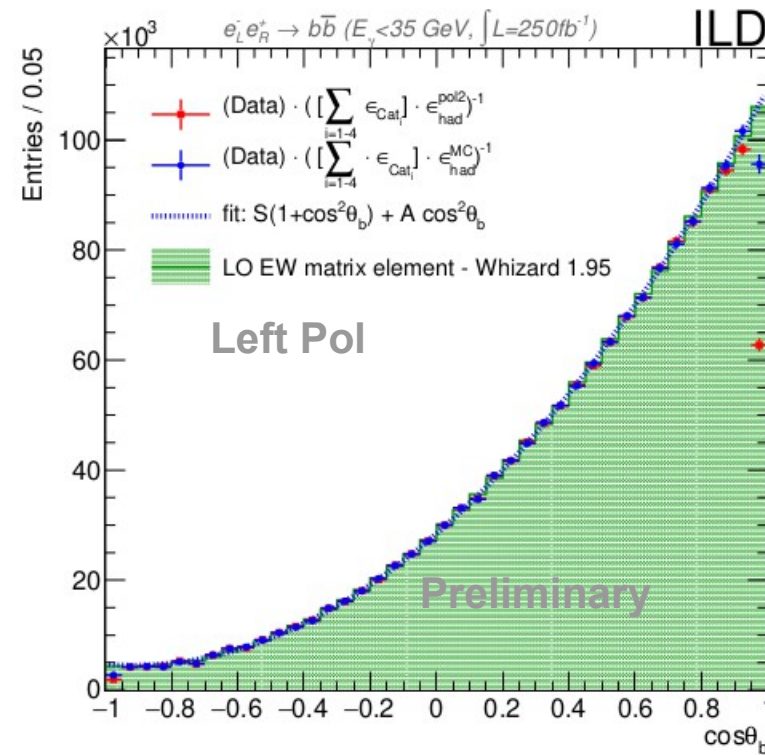
*Semi-leptonic channel*



ILD-Note-2019-007

- Integrated Luminosity  $4 \text{ fb}^{-1}$
- Exact reproduction of generated spectra
- Statistical precision on cross section:  $\sim 0.1\%$
- Statistical precision on  $A_{FB}$ :  $\sim 0.5\%$
- Can expect that systematic errors will match statistical precision (but needs to be shown)

Arxiv:1709.04289, ILD Paper in progress  
 A. Irlès, SUSY2021



## Excellent agreement between predicted and reconstructed distributions

- Gap between red dots and green histogram = acceptance drop.
- Blue dots = corrected acceptance
- The fit is restricted to  $|\cos\theta_b| < 0.8$ 
  - *Minimal impact of the corrections*

Stat unc (2000 fb<sup>-1</sup>)

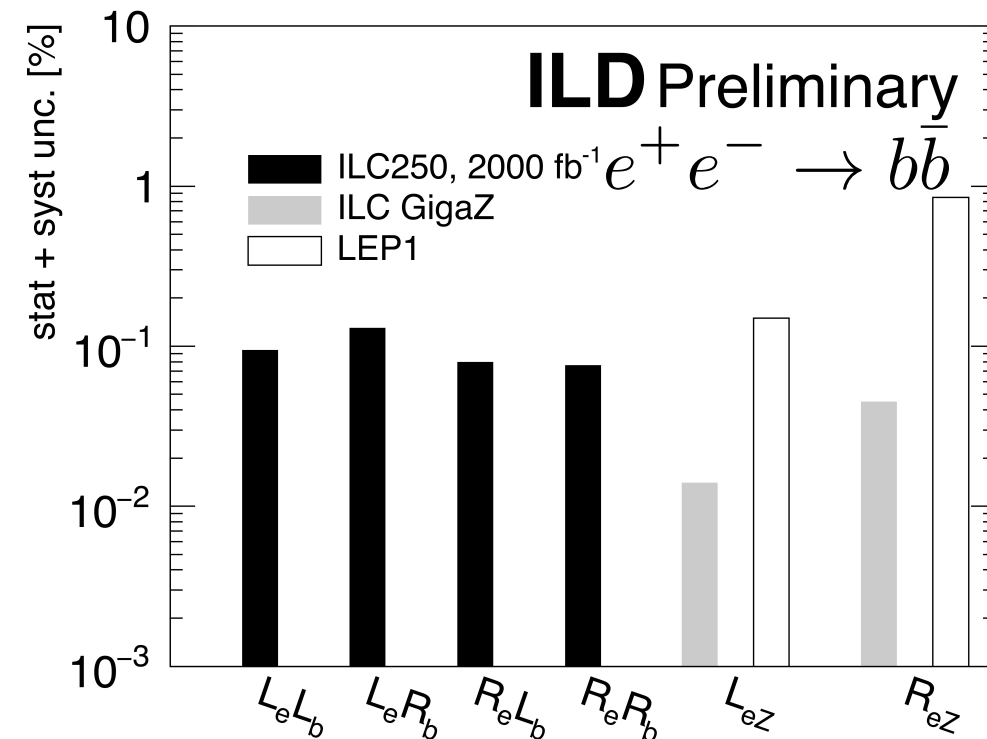
Syst unc.:

- Selection and background rejection
- quark tagging/mistagging (modélisation, QCD, correlations)
- Luminosity
- Polarisation

	Beam Polarisation	
	(-+)	(+-)
$R_b^{cont.}$	$0.173 \pm 0.12\% \text{ (stat.)} \pm 0.14\% \text{ (syst.)}$	$0.130 \pm 0.15\% \text{ (stat.)} \pm 0.13\% \text{ (syst.)}$
$A_{FB}^{b\bar{b}}$	$0.6823 \pm 0.15\% \text{ (stat.)} \pm 0.06\% \text{ (syst.)}$	$0.3487 \pm 0.75\% \text{ (stat.)} \pm 0.29\% \text{ (syst.)}$



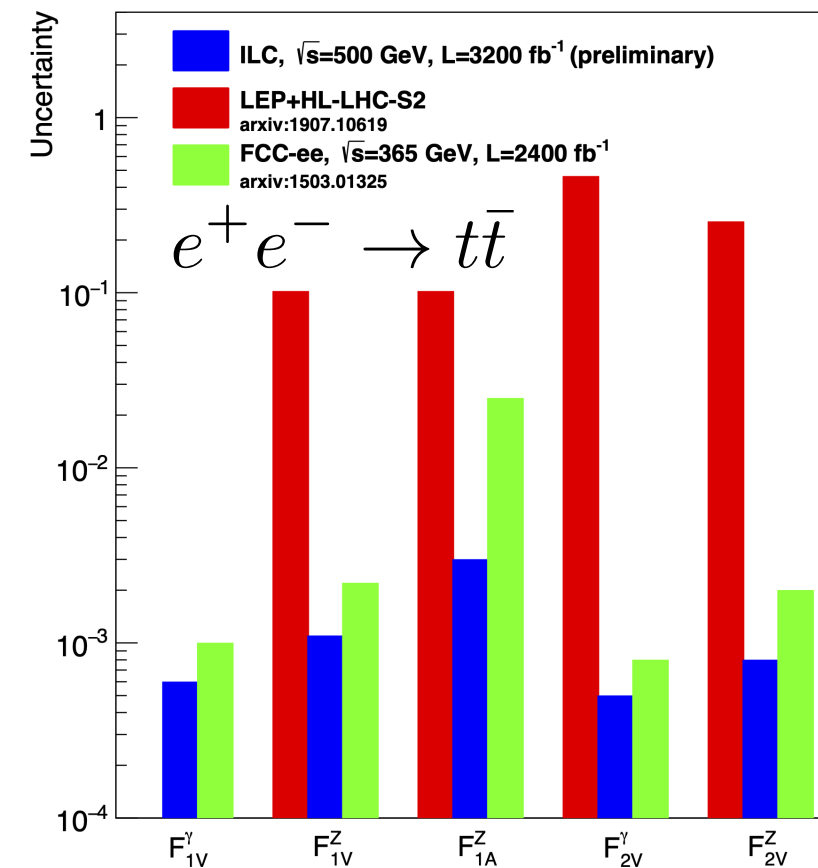
Arxiv:1709.04289, ILD Paper in progress



Couplings are order of magnitude better than at LEP

$$\text{LeLb} = Q_e Q_b + \frac{L_e Z L_b Z}{s^2 w c^2 w} BWZ + \sum_{Z'} \frac{L_e Z' L_b Z'}{s^2 w c^2 w} BWZ'$$

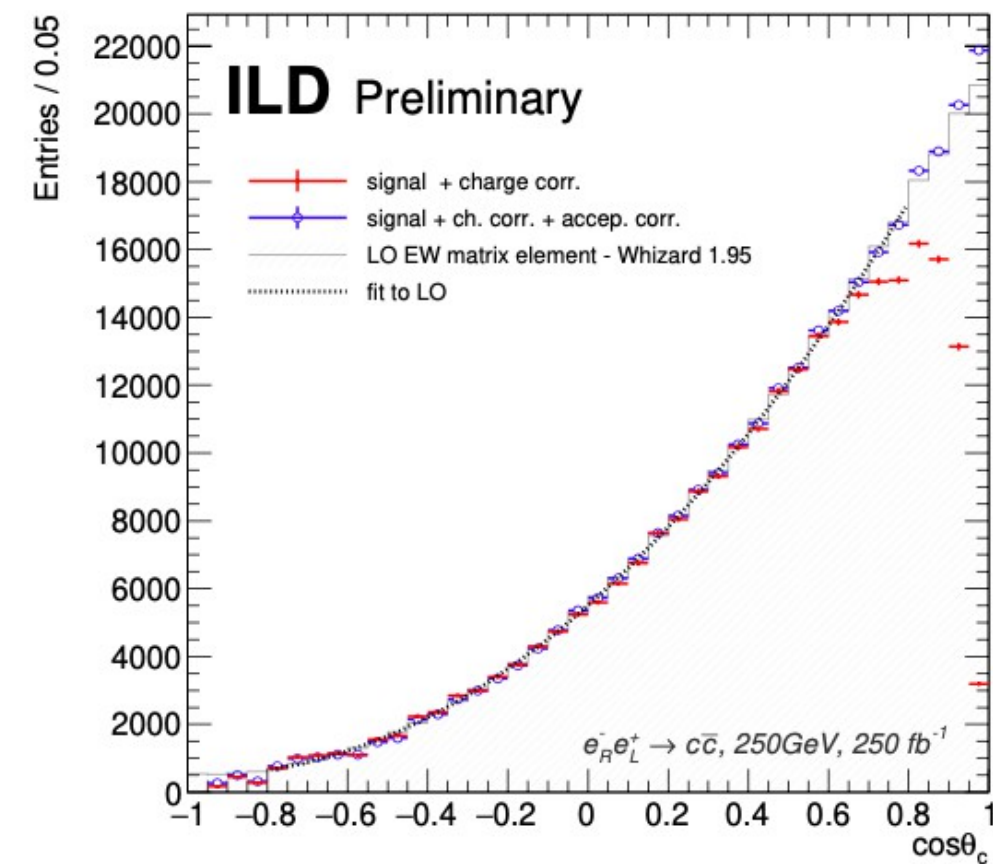
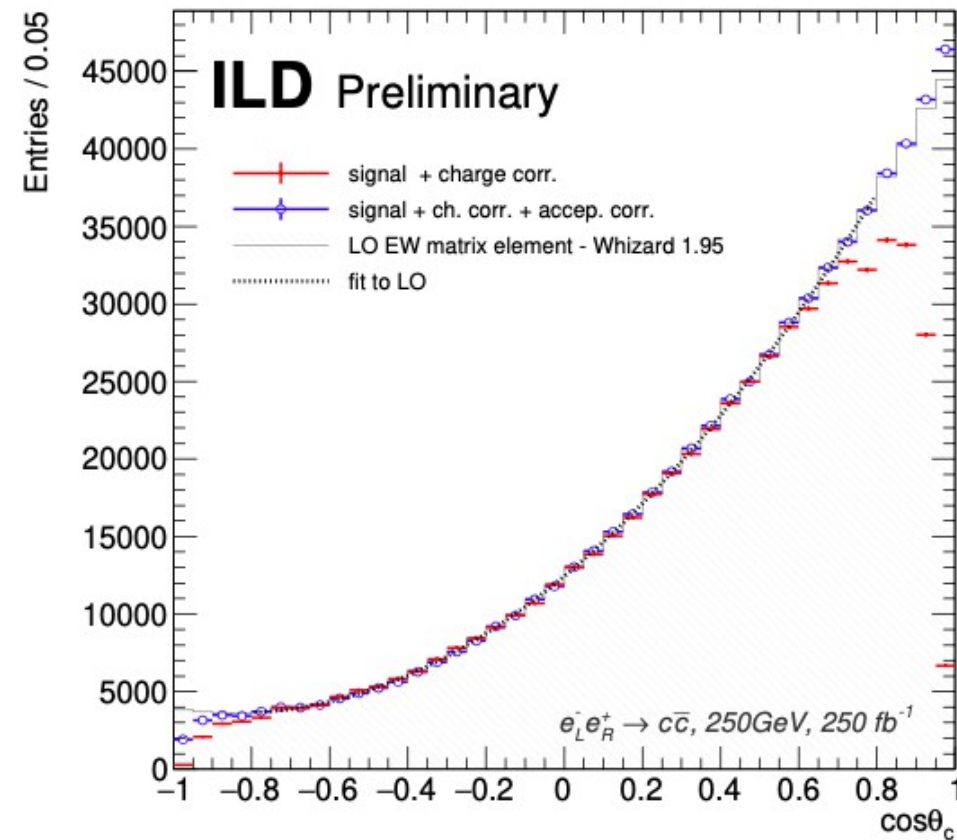
ILC250      SM      GigaZ      New resonances



- e<sup>+</sup>e<sup>-</sup> collider way superior to LHC (sqrt(s) = 14 TeV)
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime
  - Less systematic uncertainties
  - Axial form factors are ~ and benefit therefore from higher energies

Full disentangling of helicity structure for all fermions only possible with polarised beams!!

arxiv:2002.05805

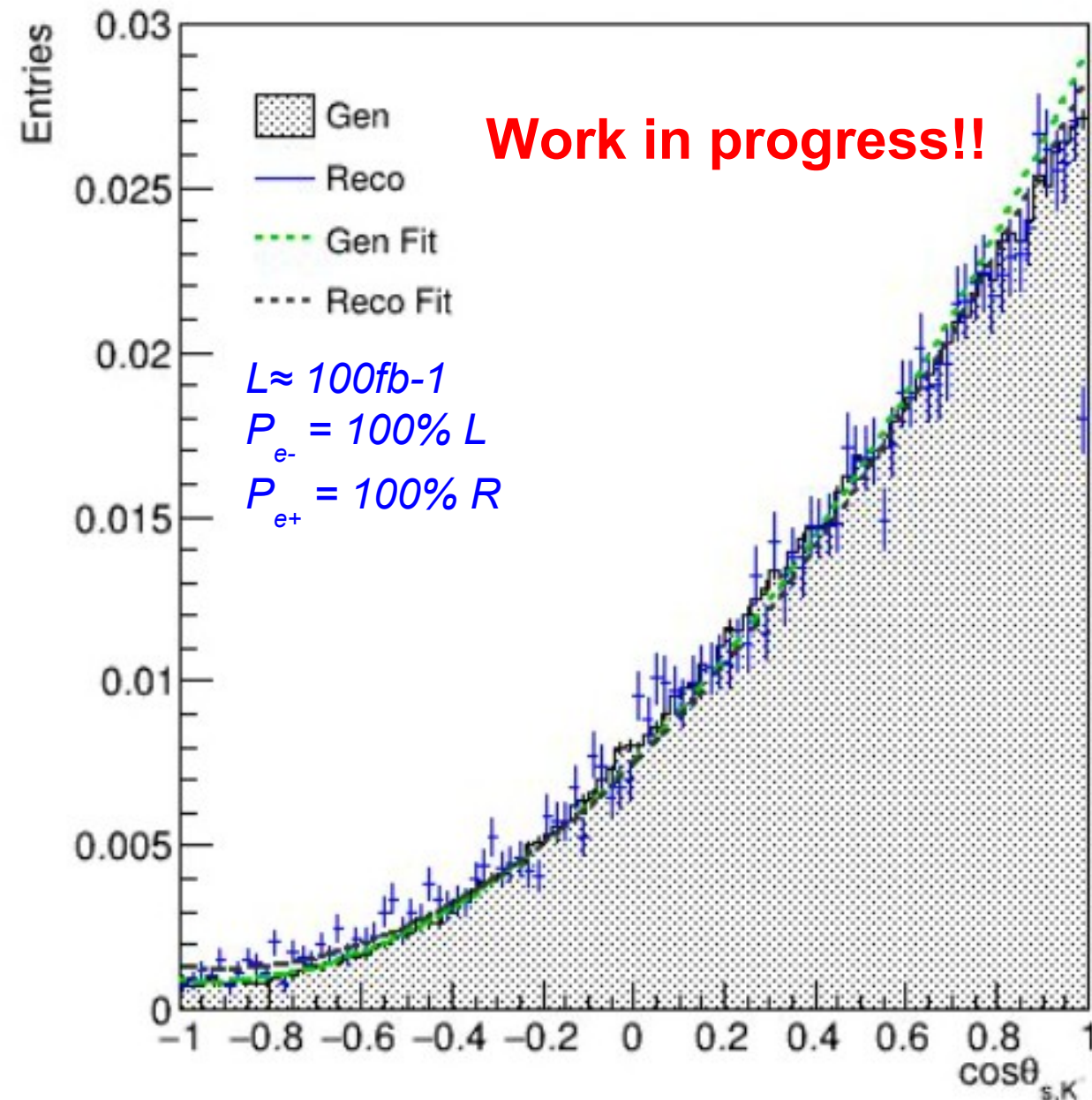


Full simulation study (with ILD concept)  
 Long lever arm in  $\cos \theta_c$  to extract from factors or couplings



*Y. Okugawa, F. Richard, A. Irlès, R.P.*

Full simulation with ILD s/w framework



- This is just an appetiser!
- Analysis is very early stage
  - Full simulation and reconstruction but preselection based on MC truth
  - Analysis will consolidate during Snowmass process!
- Backbone is selection of charged Kaon
  - Strict requirement that charged Kaon with  $P_K > 10 \text{ GeV}$  is leading particle in jet
- Need to control backgrounds from  $ee \rightarrow uu$  and  $ee \rightarrow dd$
- Will complete picture on  $ee \rightarrow qq$ 
  - The rest is  $uu/dd$  that will be indistinguishable and will have to be treated together
- Excellent benchmark for detector
  - “Particle ID is King”

	$\sqrt{s}$ -250 GeV	Threshold	Continuum ( $\geq 380$ GeV)	Comment
ee->tt (electroweak)	N/A	Not covered	Not covered	<ul style="list-style-type: none"> <li>• ILC/CLIC Papers exist</li> <li>• CLIC380 close(r) to threshold</li> <li>• ee-&gt;tt fully hadronic is not covered (and difficult!)</li> <li>• ee-&gt;tt semi-leptonic needs re-assessment of systematic uncertainties</li> </ul>
ee->tt (top mass)	N/A	Not covered	Covered	<ul style="list-style-type: none"> <li>• Many studies and papers exist</li> <li>• However uncovered aspects (AFB, at threshold, polarisation effects, ...)</li> <li>• Top mass in continuum requires full sim. study</li> </ul>
ee->bb	Covered		Covered	<ul style="list-style-type: none"> <li>• 250 GeV: paper publication in progress</li> <li>• 500 GeV freshly started</li> </ul>
ee->cc	Covered		Covered	<ul style="list-style-type: none"> <li>• 250 GeV: paper publication in progress</li> <li>• 500 GeV freshly started</li> </ul>
ee->ss	Covered		Not covered	<ul style="list-style-type: none"> <li>• 250 GeV: freshly started</li> </ul>

The picture is likely to be incomplete! Please let me know if everything is missing

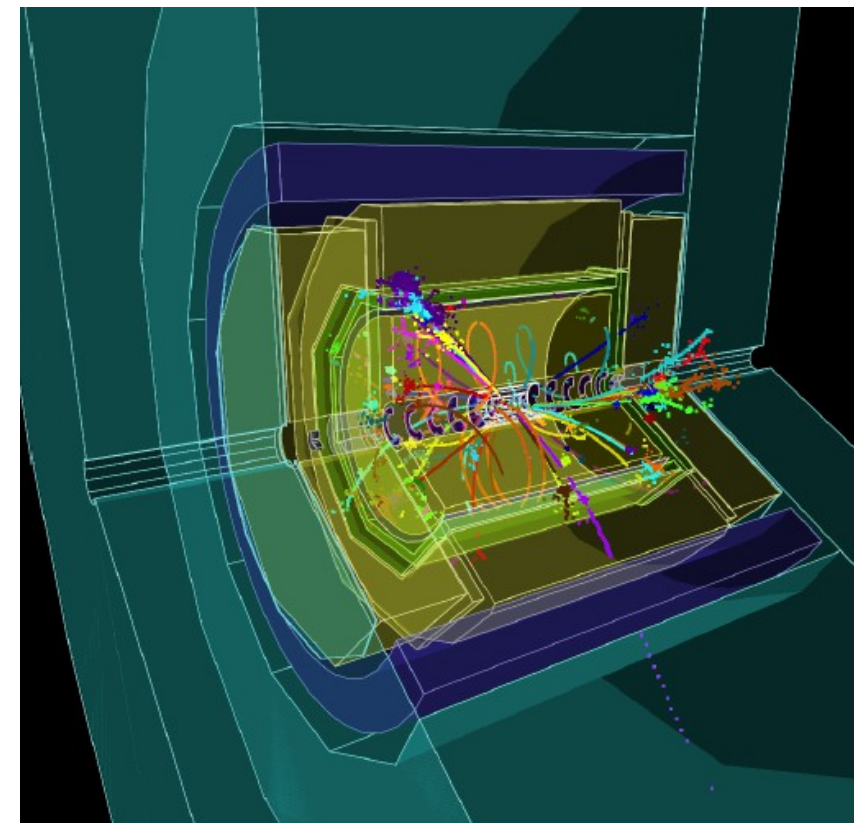
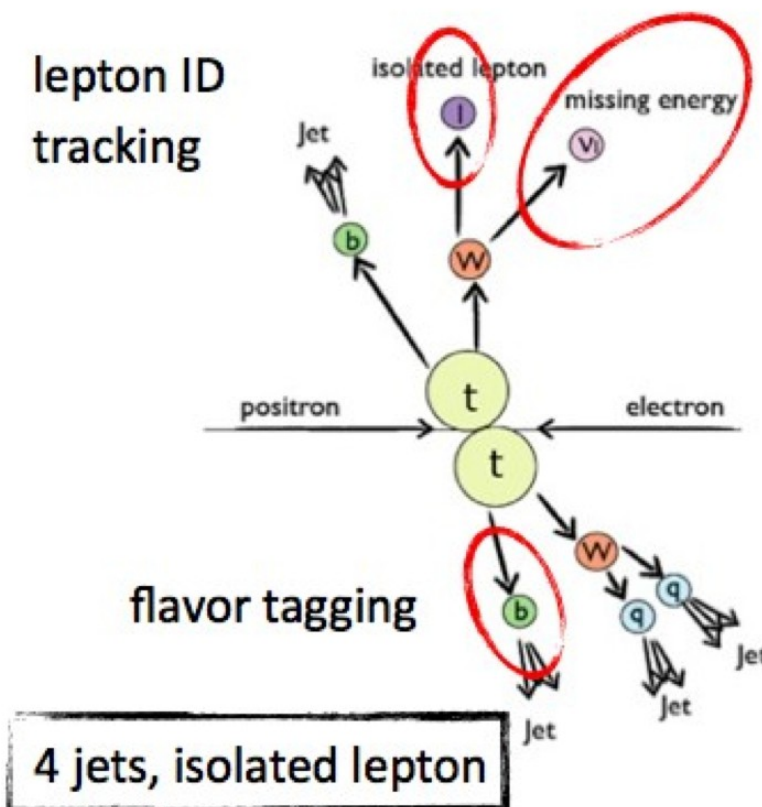
- Linear colliders are ideally suited for precision measurements of two-fermion final states
- Measurement of top mass to a precision of  $\sim 50$  MeV in clean environment
  - Flexibility in energy allow for complementary methods
  - Threshold scan and radiative events
  - Watch out for new ideas later today
- Linear colliders will have the answer whether new physics acts on heavy doublet (t,b) only or on all fermions
- Will/would probe helicity structure of electroweak fermion couplings over at least one order of magnitude in energy (Z-Pole  $\rightarrow \sim 1$  TeV)
  - Achievable experimental precisions  $\sim 0.1 - 1\%$
  - Effects may become already visible at 250 GeV stage for b quark and c quarks (and other light fermions)
  - Amplification of effects at higher energies
  - Clear and unique pattern thanks to polarised beams
- Active phenomenological studies in terms of global analyses (EFT) and concrete models
- Main challenge at future machines will be the control of systematic errors
  - Experimentally
    - Vertex charge and particle ID
    - PFO for final state jets
  - Theoretically (not discussed)
    - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results

Backup

Three different final states:

- 1) Fully hadronic (46.2%) → 6 jets
- 2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
- 3) Fully leptonic (10.3%) → 2 jets + 4 leptons

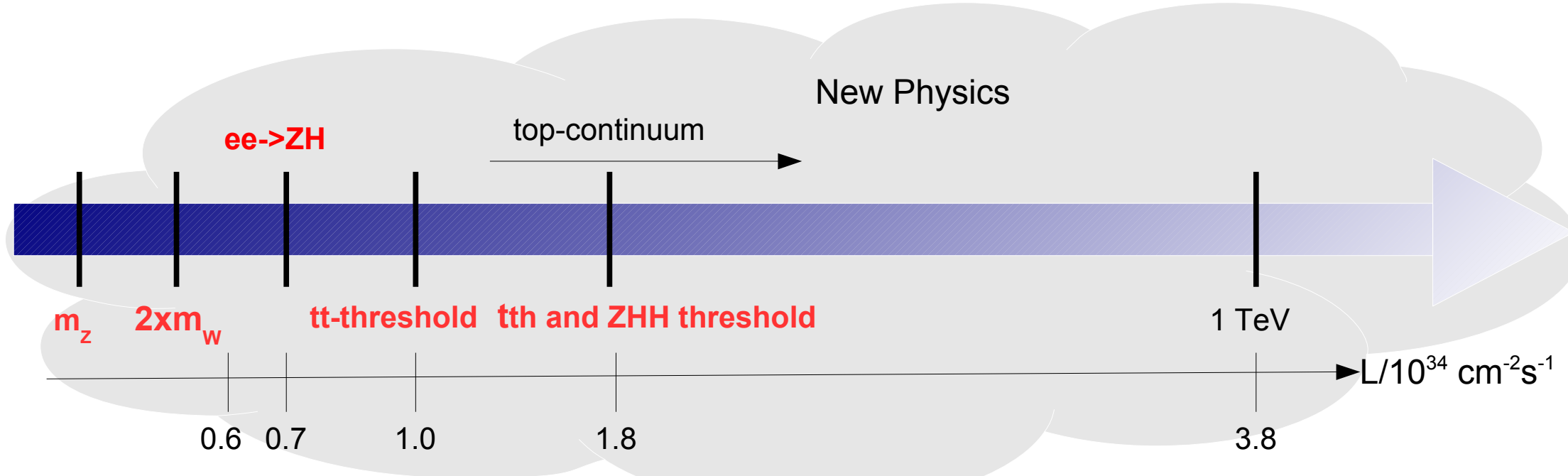
$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(bl\nu)$$



Final state reconstruction uses all detector aspects

Results shown in the following are based on full simulation of LC Detectors





All Standard Model particles within reach of planned linear colliders

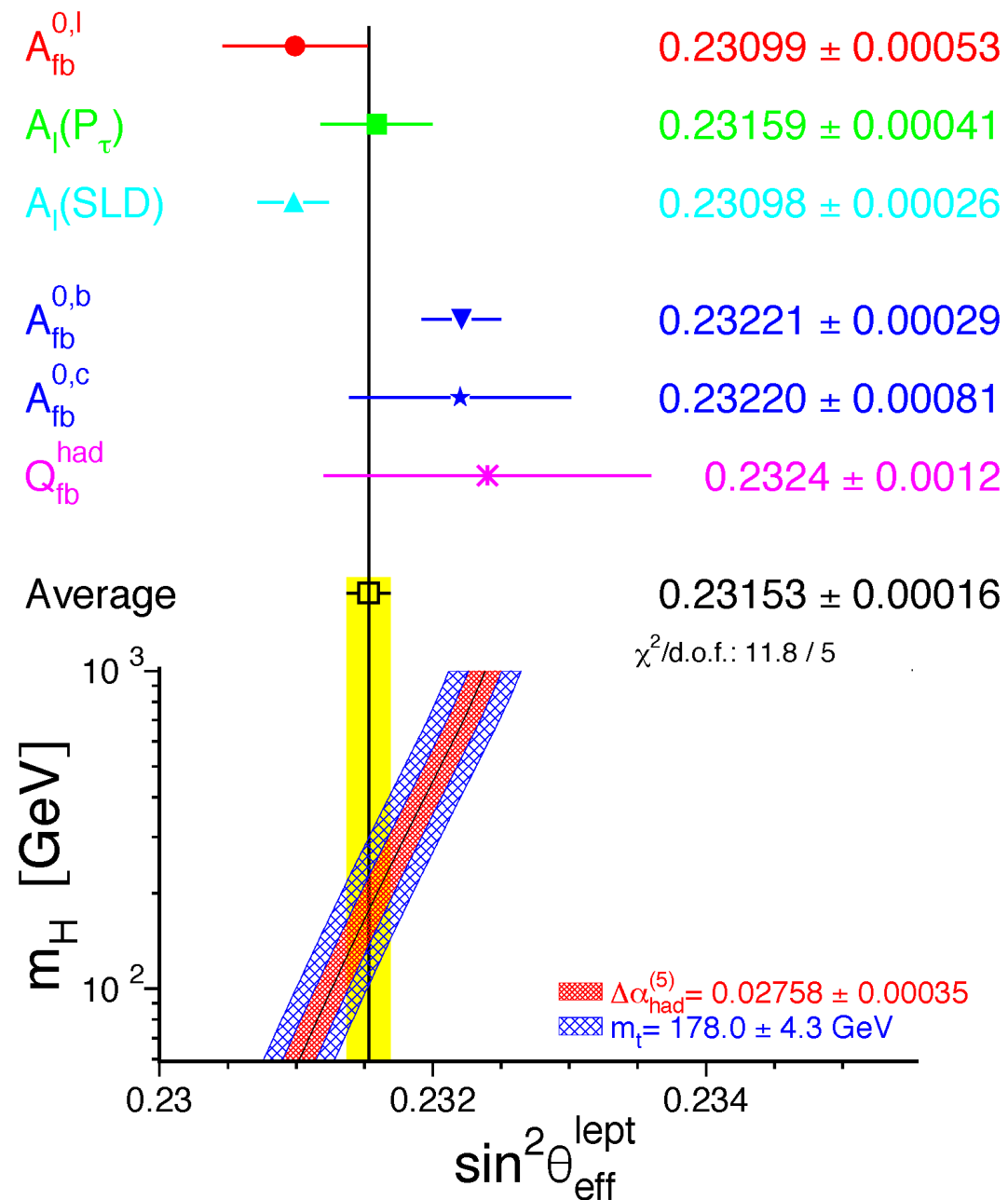
High precision tests of Standard Model over wide range to detect onset of New Physics

Machine settings can be “tailored” for specific processes

- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4} [(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

**Background free** searches for BSM through beam polarisation



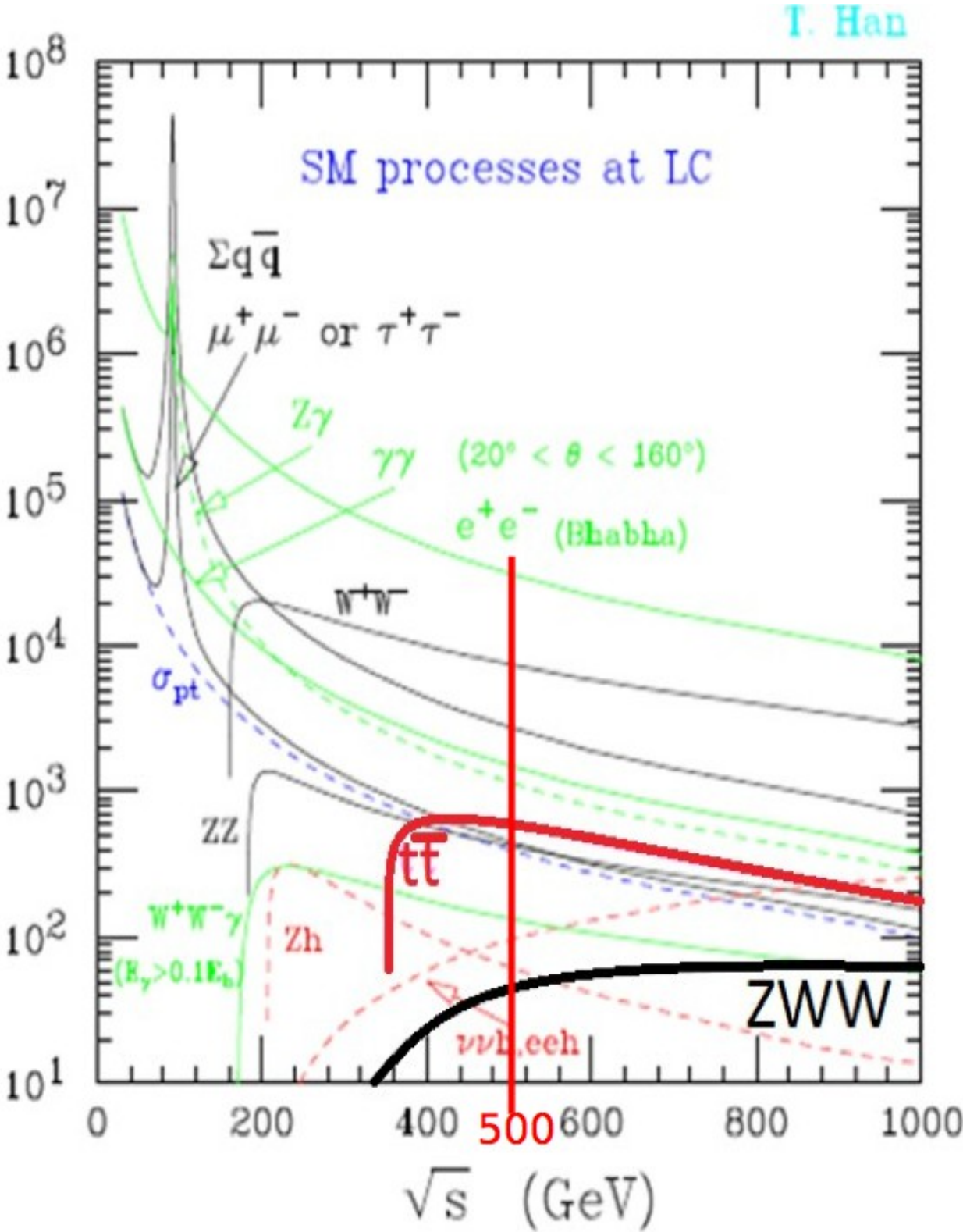
Most precise single Individual determination of  $\sin^2 \theta_{\text{eff}}^{\ell}$  from SLC

- Left-right asymmetry of leptons

- Most precise measurement of  $\sin^2 \theta_{\text{eff}}^{\ell}$  from forward backward asymmetry  $A_{FB}^b$  in  $ee \rightarrow bb$  at LEP

:

- Most precise determinations of  $\sin^2 \theta_{\text{eff}}^{\ell}$  differ significantly
  - Requires verification
  - **Heavy quark effect, effect on all quarks/fermions, no effect at all?**



$$e^+e^- \rightarrow t\bar{t} : \quad 500 \text{ GeV}$$

Channel	$\sigma_{unpol.}$ [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]
$t\bar{t}$	572	1564	724
$\mu^+\mu^-$	456	969	854
$\sum_{q=u,d,s,c} q\bar{q}$	2208	6032	2793
$b\bar{b}$	372	1212	276
$\gamma Z^0$	11185	25500	19126
$W^+W^-$	6603	26000	150
$Z^0Z^0$	422	1106	582
$Z^0W^+W^-$	40	151	8.7
$Z^0Z^0Z^0$	1.1	3.2	1.22
Single $t$ for $e^+e^- \rightarrow e^- \bar{\nu}_e t \bar{b}$ [11]	3.1	10.0	1.7

352 GeV (unpol)

450 fb

25.2 pb

11.5 pb  
865 fb

$$e^+e^- \rightarrow b\bar{b} : \quad 250 \text{ GeV}$$

Channel	$\sigma_{unpol}$ fb	$\sigma_L$ fb	$\sigma_R$ fb
$b\bar{b}$	1756	5629	1394
$\gamma b\bar{b}$ (Z return)	7860	18928	12512
ZZ hadronic with $b\bar{b}$	196	549	236
HZ hadronic with $b\bar{b}$	98	241	152

$$e^+e^- \rightarrow c\bar{c} : \quad 250 \text{ GeV}$$

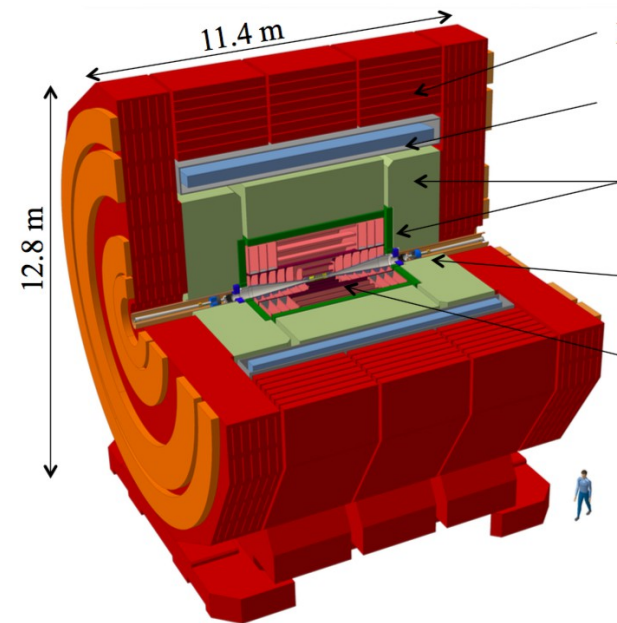
$$\sigma(P_{e^-} = -1, P_{e^+} = +1) \approx 8518 \text{ fb}$$

$$\sigma(P_{e^-} = +1, P_{e^+} = -1) \approx 3565 \text{ fb}$$

$$\sigma_{unpol.} \approx 3020 \text{ fb}$$

e+e- detector concepts for linear colliders  
 Preferred solution Particle Flow Detectors

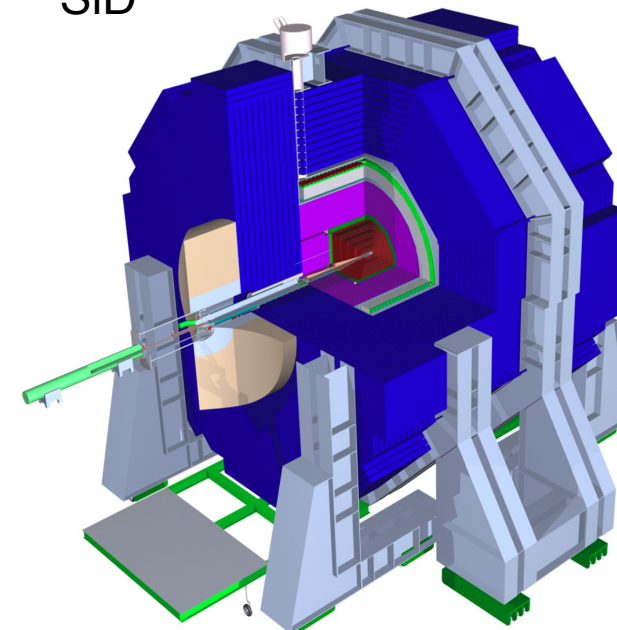
CLIC Detector



$B = 4\text{T}$

Central tracking with silicon

SiD

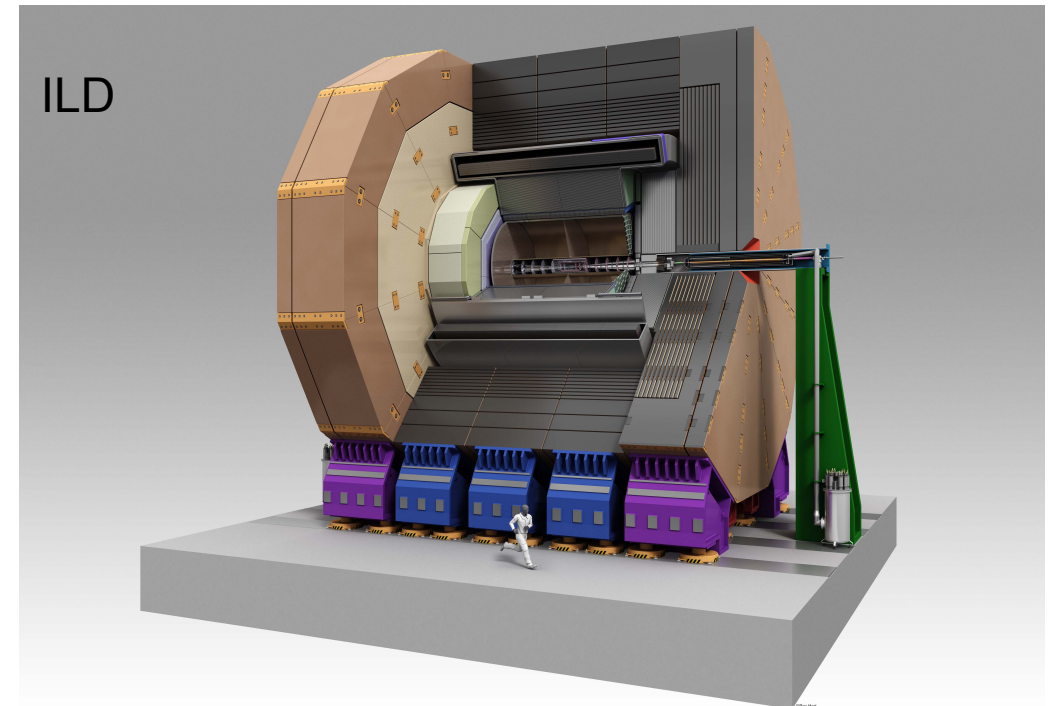


$B = 5\text{T}$

Highly granular calorimeters

Inner tracking with silicon

ILD



$B = 3.5\text{T}$

Central tracking with TPC



Track momentum:  $\sigma_{1/p} < 5 \times 10^{-5}/\text{GeV}$  (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter:  $\sigma_{d0} < [5 \oplus 10/(p[\text{GeV}]\sin^{3/2}\theta)] \mu\text{m}$  (1/3 x SLD)

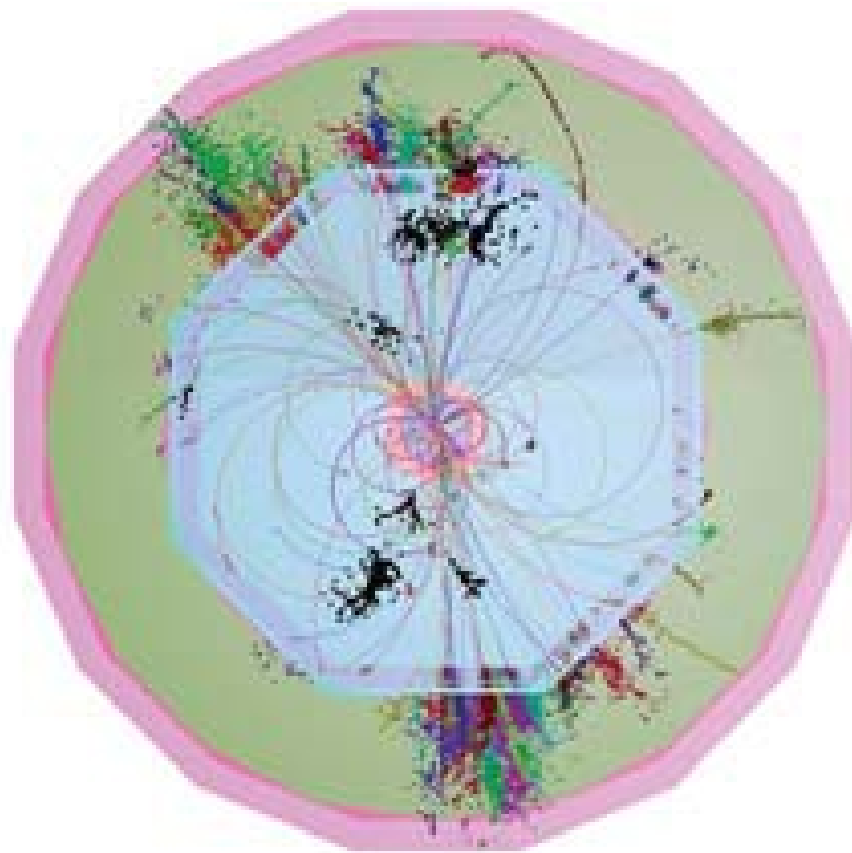
(Quark tagging c/b)

Jet energy resolution :  $dE/E = 0.3/(E(\text{GeV}))^{1/2}$  (1/2 x LEP)

(W/Z masses with jets)

Hermeticity :  $\theta_{\min} = 5 \text{ mrad}$

(for events with missing energy e.g. SUSY)



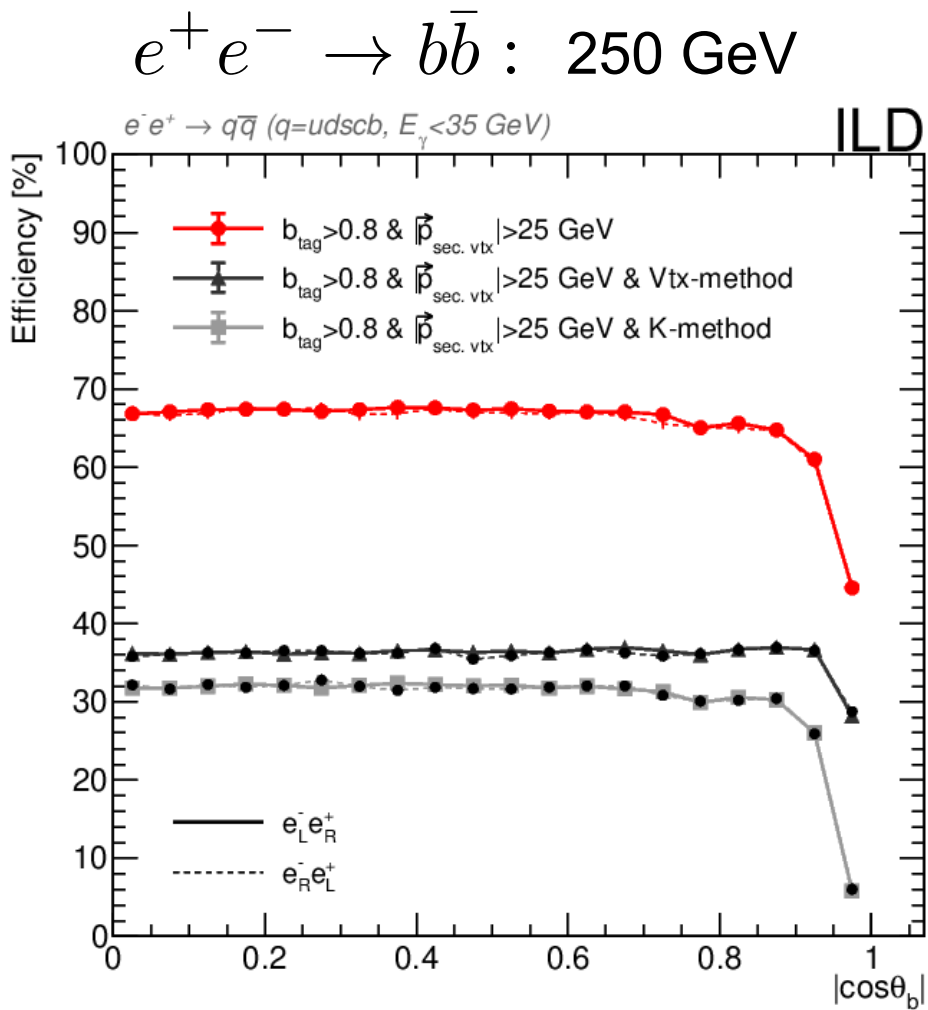
Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp





- Individual efficiency for correct b-tag and charge measurements using Vtx and Kaon charge
- Final efficiency ~20% from combination of Vtx and Kaon charge in different/same jets

$e_L^- e_R^+ \rightarrow t\bar{t}$ at 500 GeV		
General selection cuts	IDR-L	IDR-S
Isolated Lepton	92.1%	92.1%
$btag_1 > 0.8$ or $btag_2 > 0.3$	81.2%	81.1%
Thrust < 0.9	81.2%	81.1%
Hadronic mass	78.2%	78.2%
Reconstructed $m_W$ and $m_t$	73.4%	73.4%
$t$ quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^\ell > 2.4$	62.2%	61.8%
$ p_{B,had}  > 15$ GeV	34.5%	33.9%
" $t\bar{t}$ identification"	30.6%	30.2%
$b$ quark polar angle spectrum		
No additional cuts		

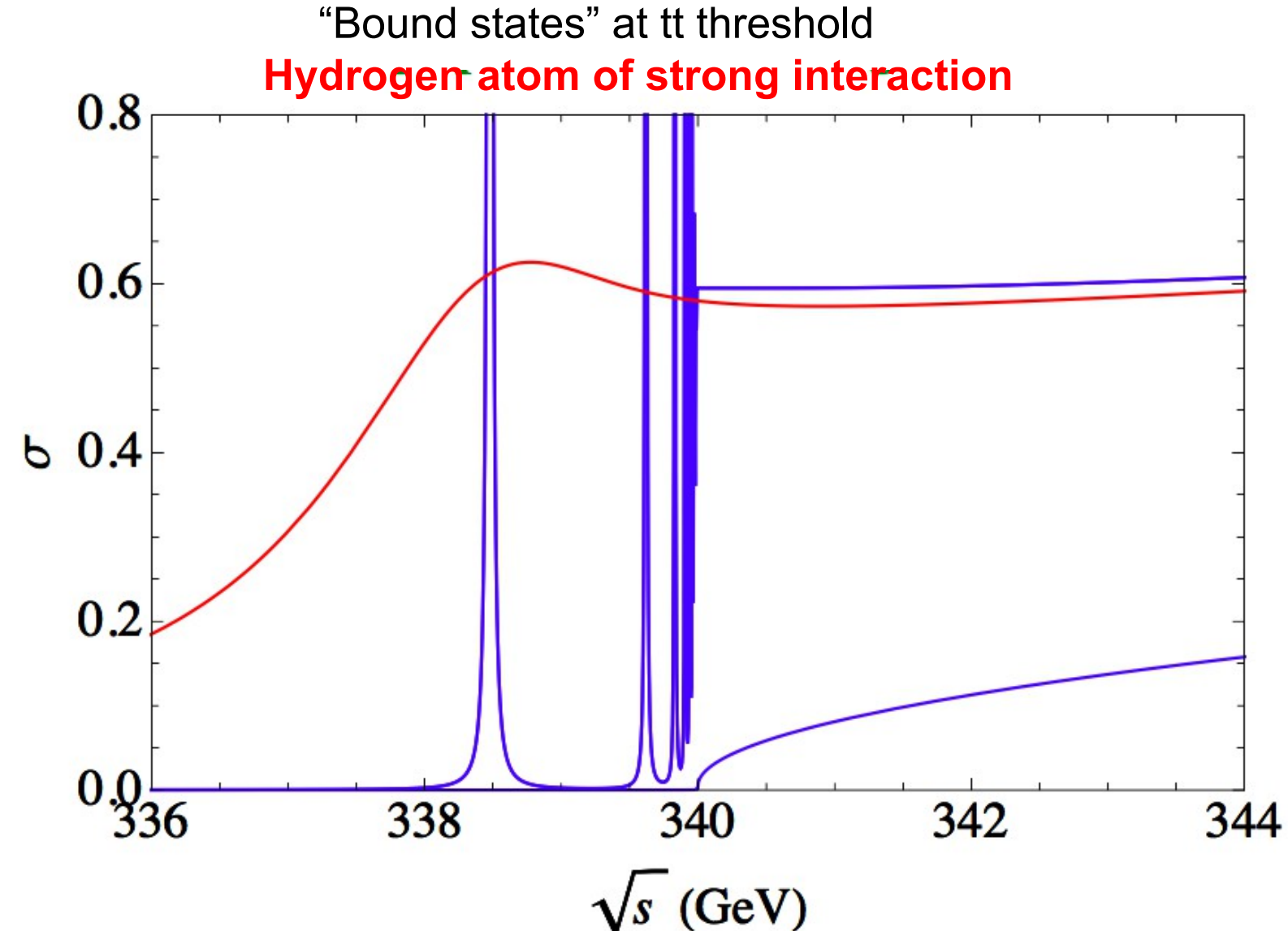
$e_R^- e_L^+ \rightarrow t\bar{t}$ at 500 GeV		
General selection cuts	IDR-L	IDR-S
Isolated Lepton	94.1%	94.0%
$btag_1 > 0.8$ or $btag_2 > 0.3$	84.9%	84.8%
Thrust < 0.9	84.9%	84.8%
Hadronic mass	82.2%	82.3%
Reconstructed $m_W$ and $m_t$	77.6%	77.5%
$t$ quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^\ell > 2.4$	64.1%	64.1%
$b$ quark polar angle spectrum		
Vtx+Vtx	10.8%	10.3%

## Total cross section

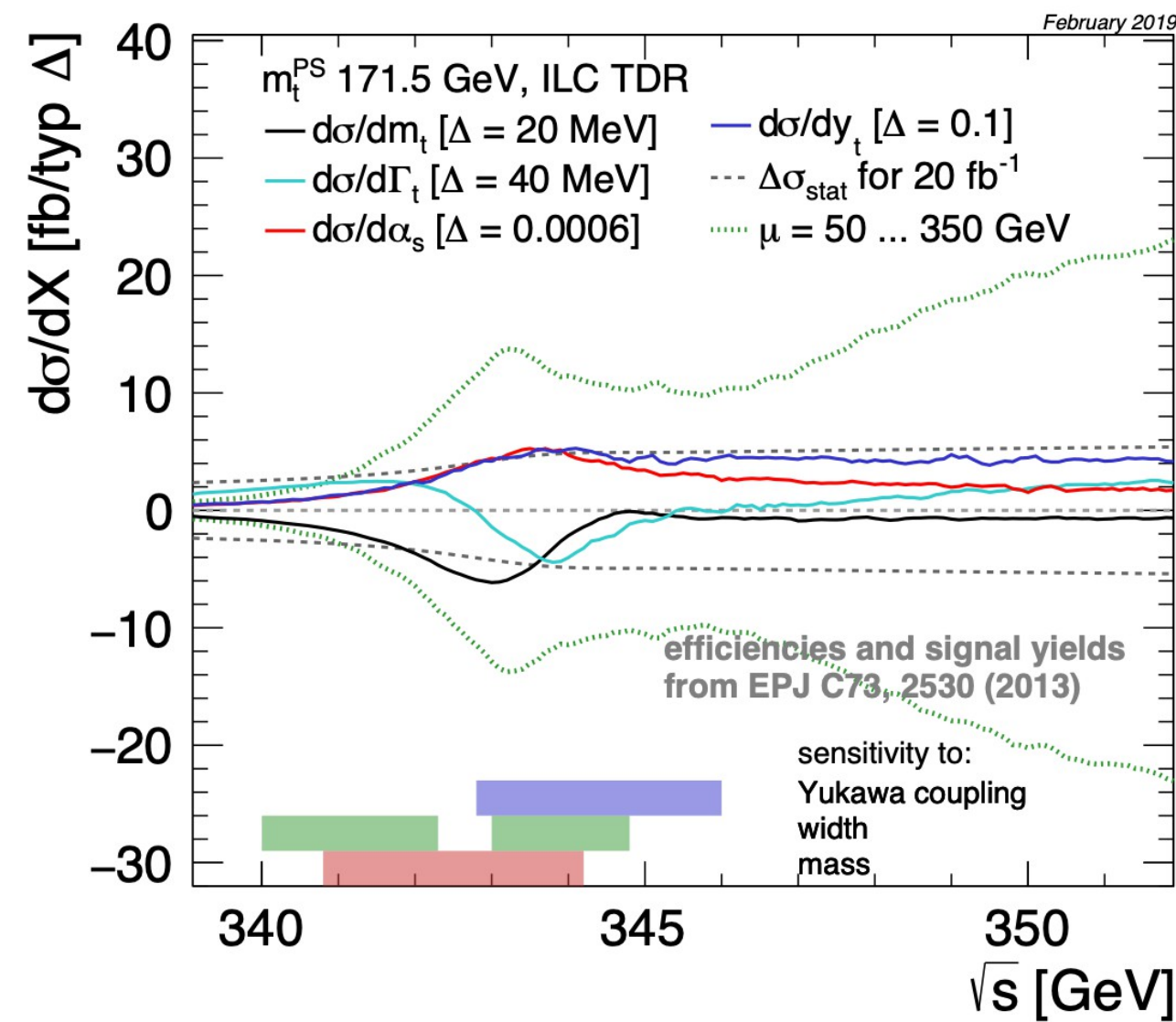
- Typical efficiency 75%
- Independent of beam polarisation

## Differential cross section

- Note, difference for different beam polarisations
- Left hand polarisation more vulnerable to migrations
- Requires information from hadronic final state
- Vtx, Kaon as in bb-case



- Size  $O(10^{-17}\text{m})$ , **smallest non-elementary object known in particle physics**  
 Small scale => Free of confinement effects => Ideal premise for precision calculations  
 Measurement of (a hypothetical)  $1^3S_1$  State
- Decay of top quark smears out resonances in a well defined way

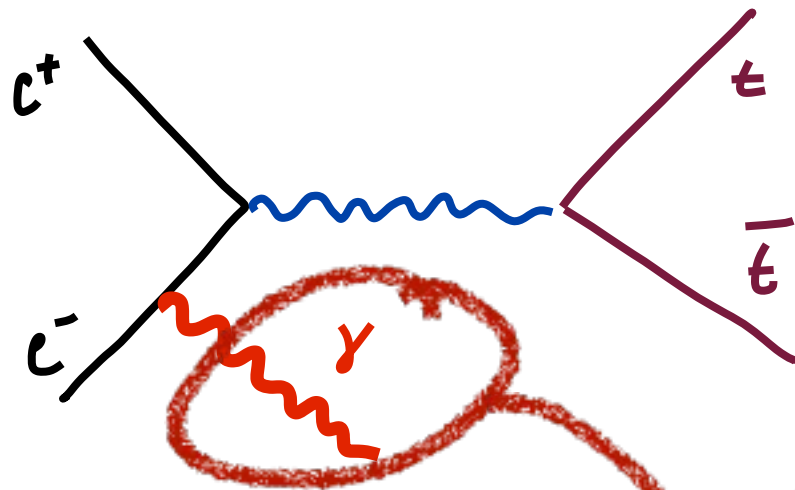


error source	$\Delta m_t^{\text{PS}} [\text{MeV}]$
stat. error ( $200 \text{ fb}^{-1}$ )	13
theory (NNNLO scale variations, PS scheme)	40
parametric ( $\alpha_s$ , current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty	< 17
combined theory & parametric	30 – 50
combined experimental & backgrounds	25 - 50
total (stat. + syst.)	40 – 75

- Detailed evaluation of systematic uncertainties
- Multi-parameter fits (mass, width,  $\alpha_s$ ,  $y_t$ ), scan optimization...

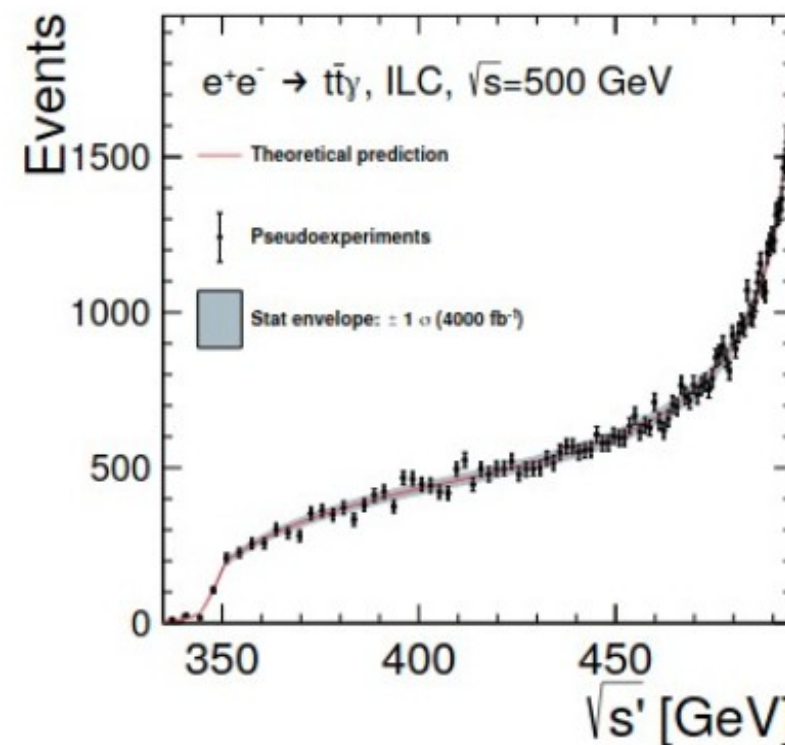
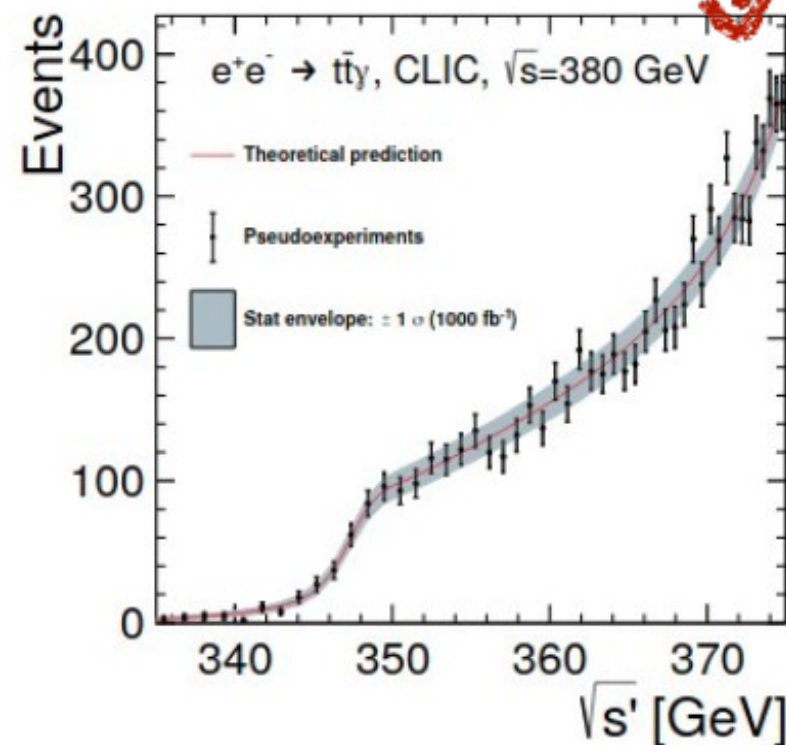


- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold

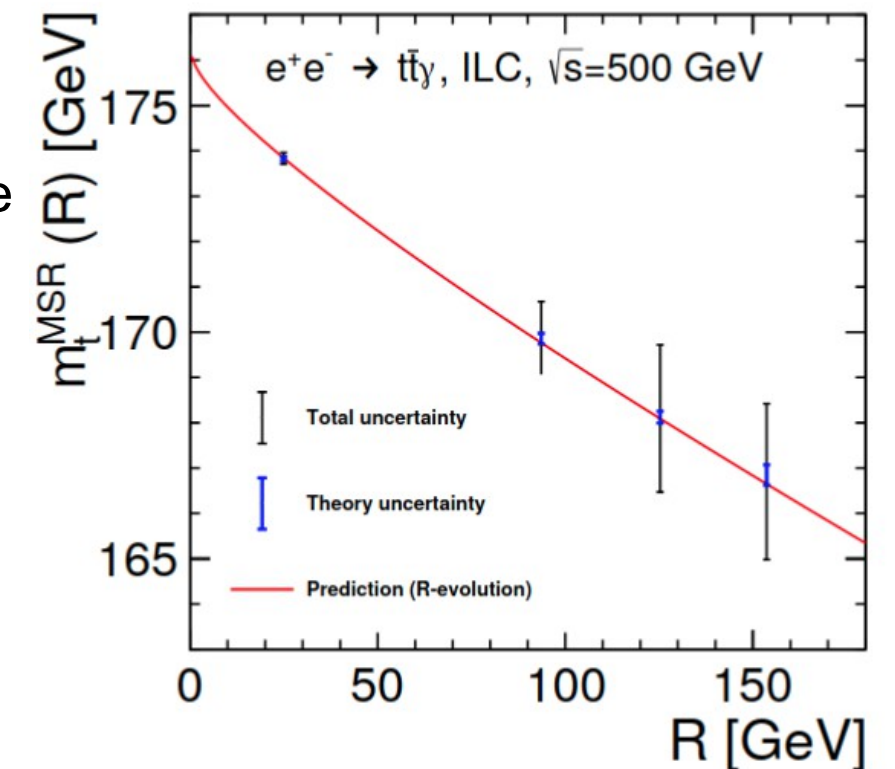


cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [ $\text{fb}^{-1}$ ]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

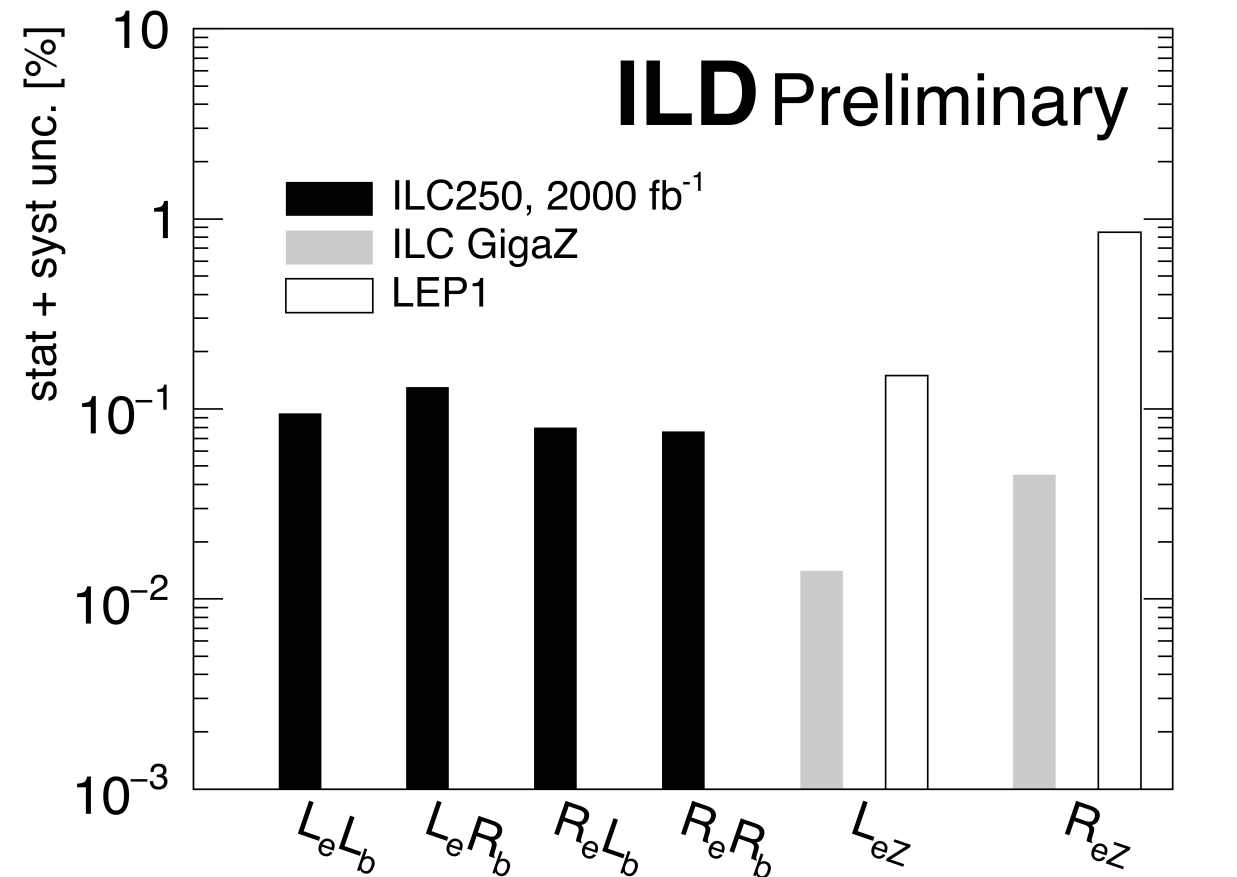
matched NNLO + NNLL calculation, luminosity  
 spectrum folded in explicitly;  
 Extraction of short distance MSR mass



can provide  $5\sigma$  evidence  
 for scale evolution  
 (“running”) of the top quark MSR  
 mass from ILC500  
 data alone



## Example b-couplings (same observation for c-couplings, arxiv:2002.05805)



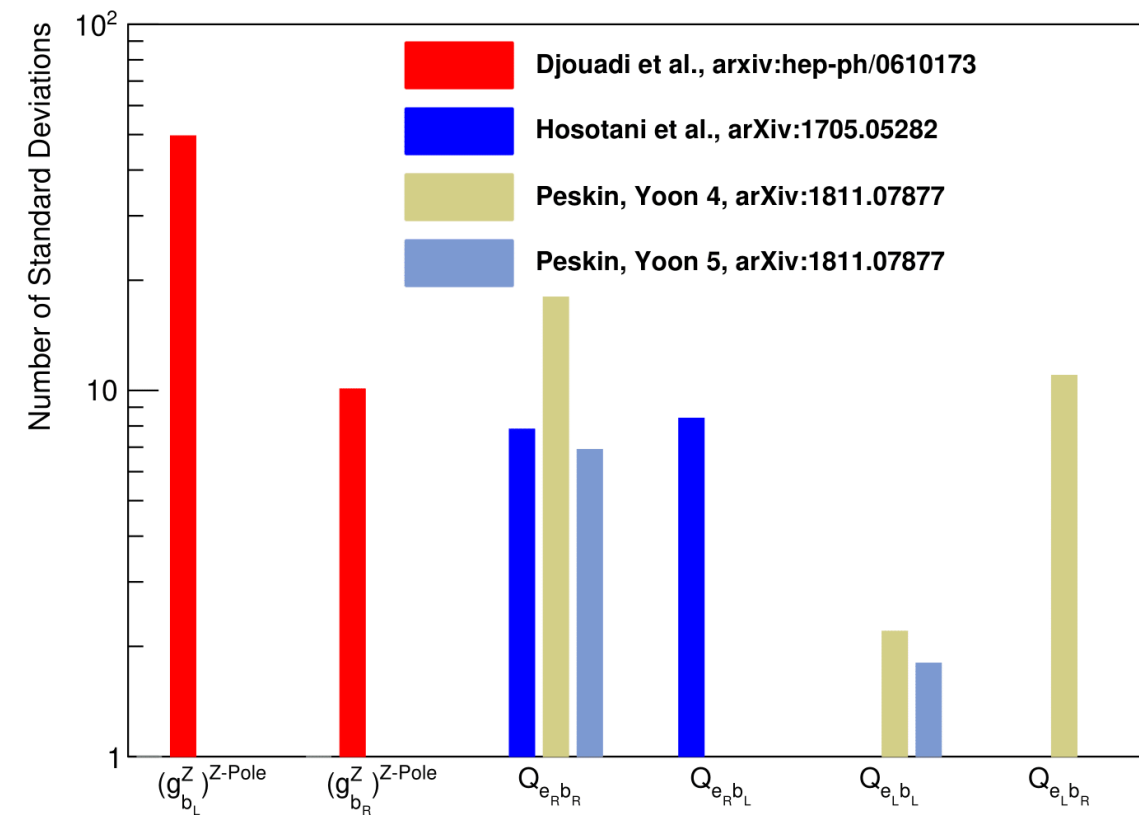
Couplings are order of magnitude better than at LEP

- In particular right handed couplings are much better constrained

New physics can also influence the Zee vertex

- in 'non top-philic' models

Full disentangling of helicity structure for all fermions only possible with polarised beams!!



Impressive sensitivity to new physics in Randall Sundrum Models with warped extra dimensions

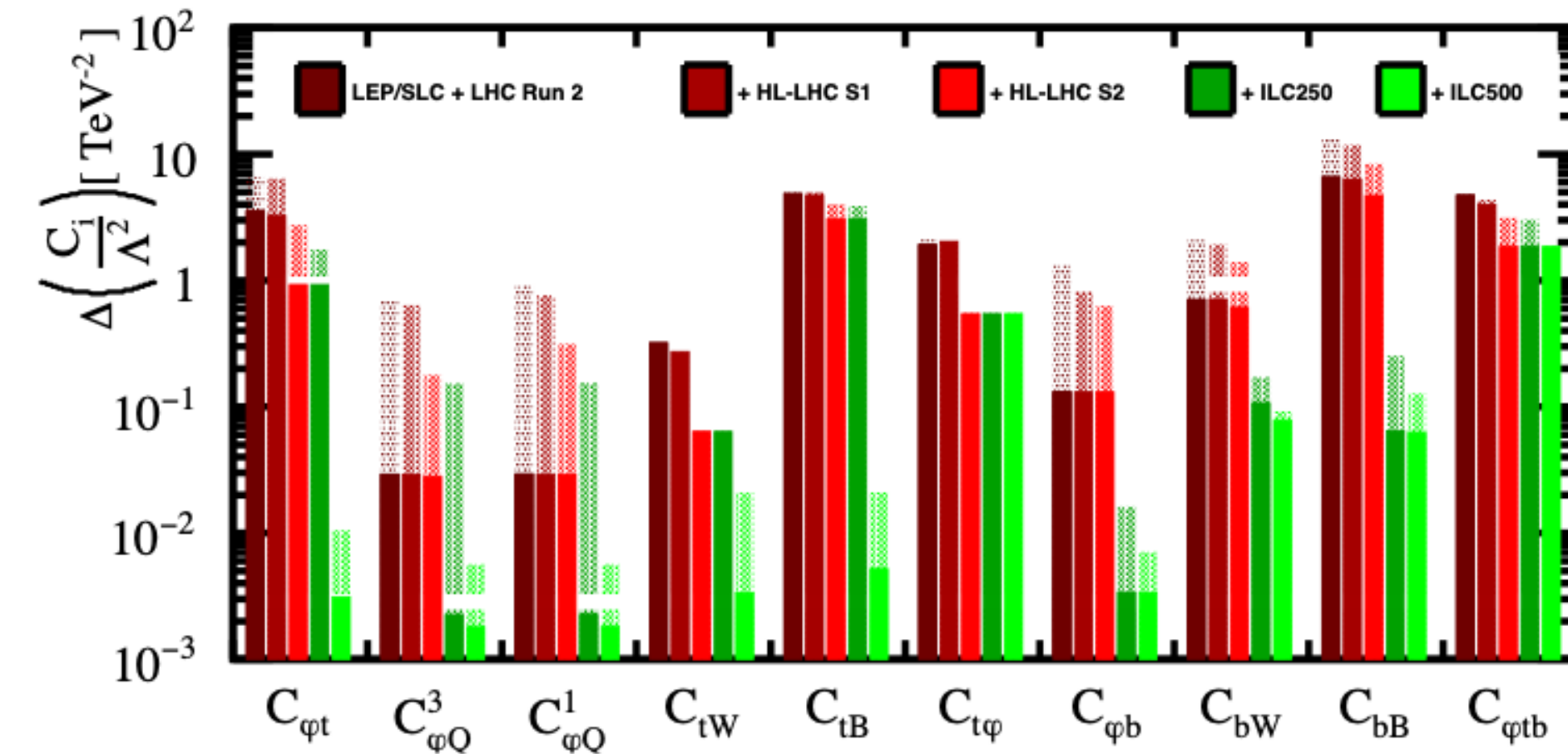
- **Complete tests only possible at LC**
- **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**

Pole measurements critical input

EF Workshop 5-6 Sept 2021 • Only poorly constrained by LEP



*arxiv:1907.10619*



Mapping between FF and EFT Coefficients

$$F_{1V}^Z = \frac{\frac{1}{4} - \frac{2}{3}s_W^2}{s_W c_W} - \frac{m_t^2}{\Lambda^2} \frac{1}{2s_W c_W} \left[ C_{\varphi q}^V = C_{\varphi u}^{(33)} + (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}) \right],$$

$$F_{1A}^Z = \frac{-\frac{1}{4}}{s_W c_W} - \frac{m_t^2}{\Lambda^2} \frac{1}{2s_W c_W} \left[ C_{\varphi q}^A = C_{\varphi u}^{(33)} - (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}) \right],$$

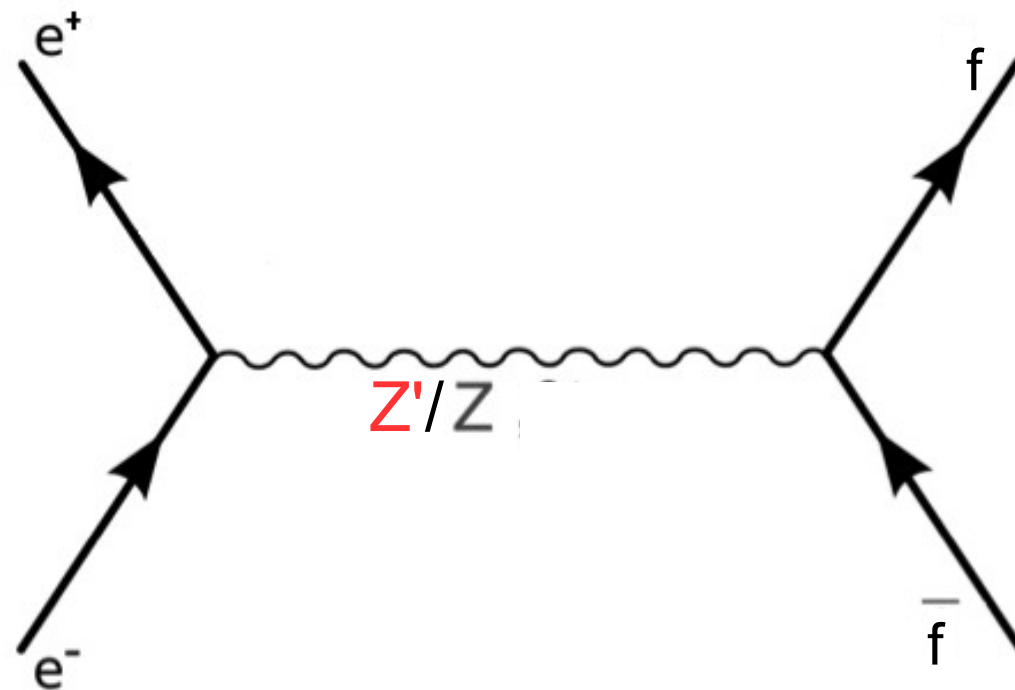
$$F_{2V}^Z = 4 \frac{m_t^2}{\Lambda^2} \left[ C_{uZ}^R = \text{Re}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\} / s_W c_W \right],$$

$$F_{2A}^Z = 4 \frac{m_t^2}{\Lambda^2} i \left[ C_{uZ}^I = \text{Im}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\} / s_W c_W \right],$$

*arxiv:1807.02121*

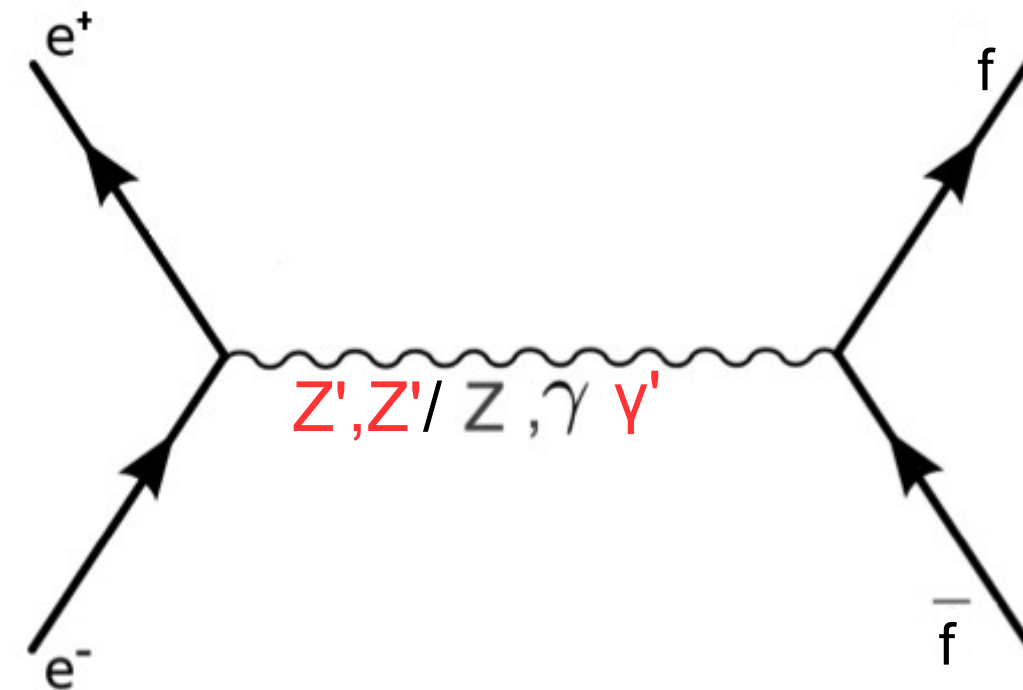
- Translation of results into EFT language confirm superiority of e<sup>+</sup>e<sup>-</sup> w.r.t. LHC
- Several operators benefit already from 250 GeV running
- Top specific operators constrained by running at 500 GeV

## On the Z-pole



- Sensitivity to  $Z/Z'$  mixing
- Sensitivity to vector (and tensor) couplings of the  $Z$ 
  - the photon does not “disturb”

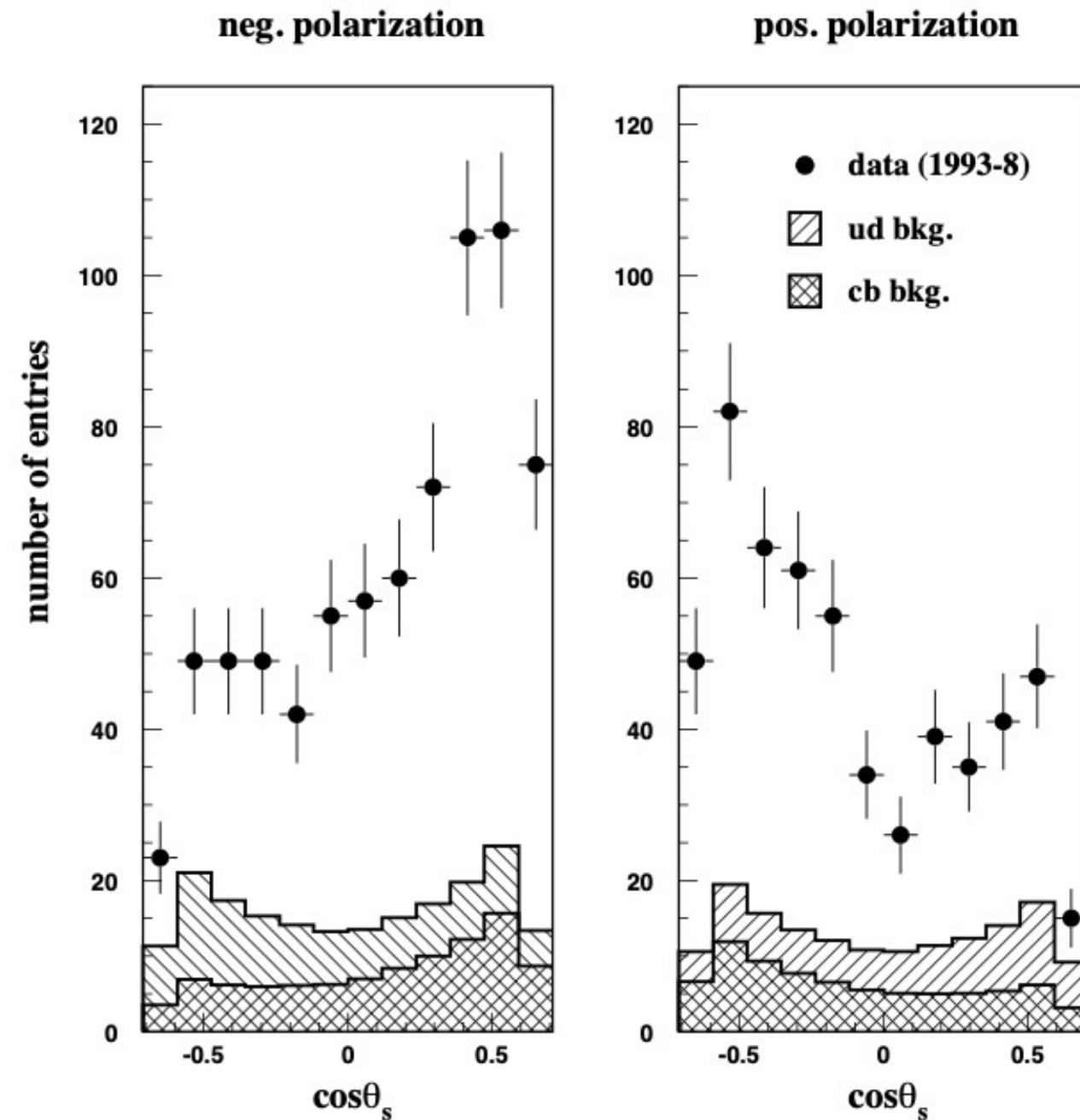
## Above the Z-pole



- Sensitivity to interference effects of  $Z$  and photon!!
- Measured couplings of photon and  $Z$  can be influenced by new physics effects
- Interpretation of result is greatly supported by precise input from  $Z$  pole

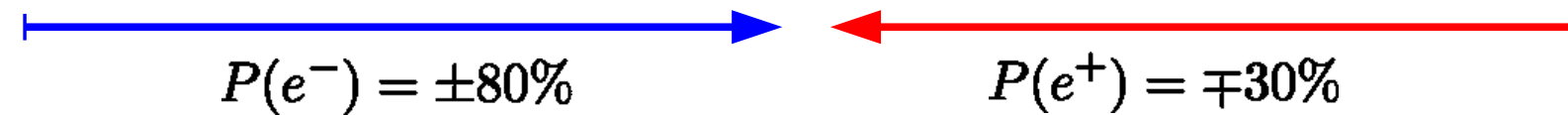
More on ILC GigaZ Program in EF04 Meeting on Friday 19/6/20

## ee -->ss: SLD Analysis at Z Pole



- Extend the heavy quark analyses to light quarks to get full picture
- Optimise vertexing and particle ID (i.e .Kaon ID with full simulation studies)

With two beam polarisation configurations



There exist a number of observables sensitive to chiral structure, e.g.

$\sigma_I$	$A_{FB,I}^t = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$	$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$
x-section	Forward backward asymmetry	Fraction of right handed top quarks

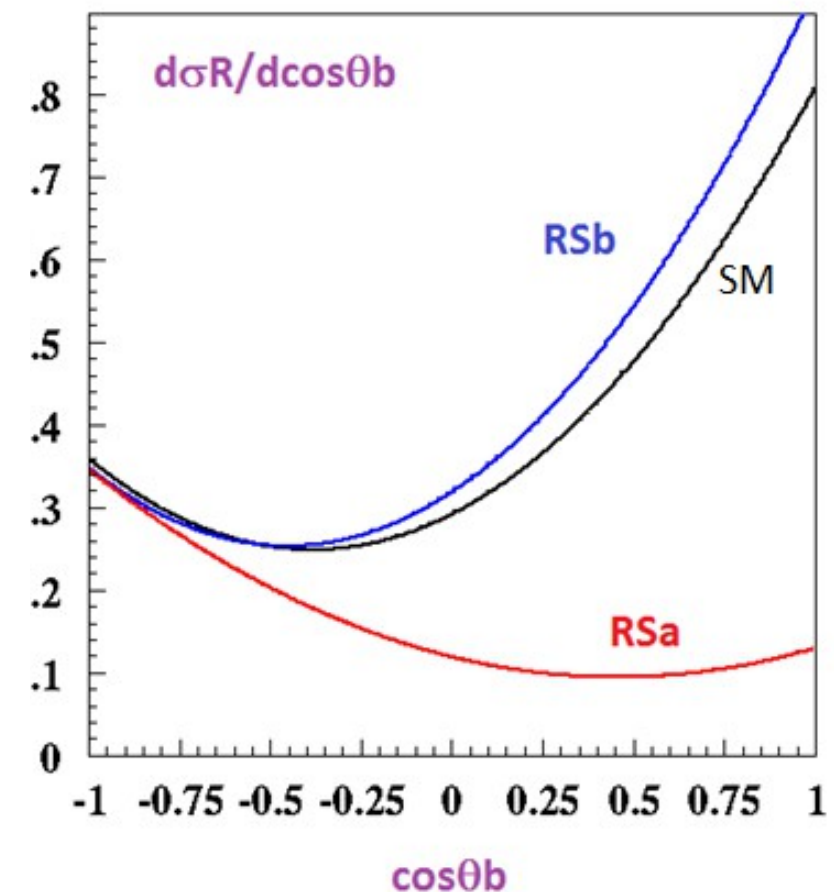
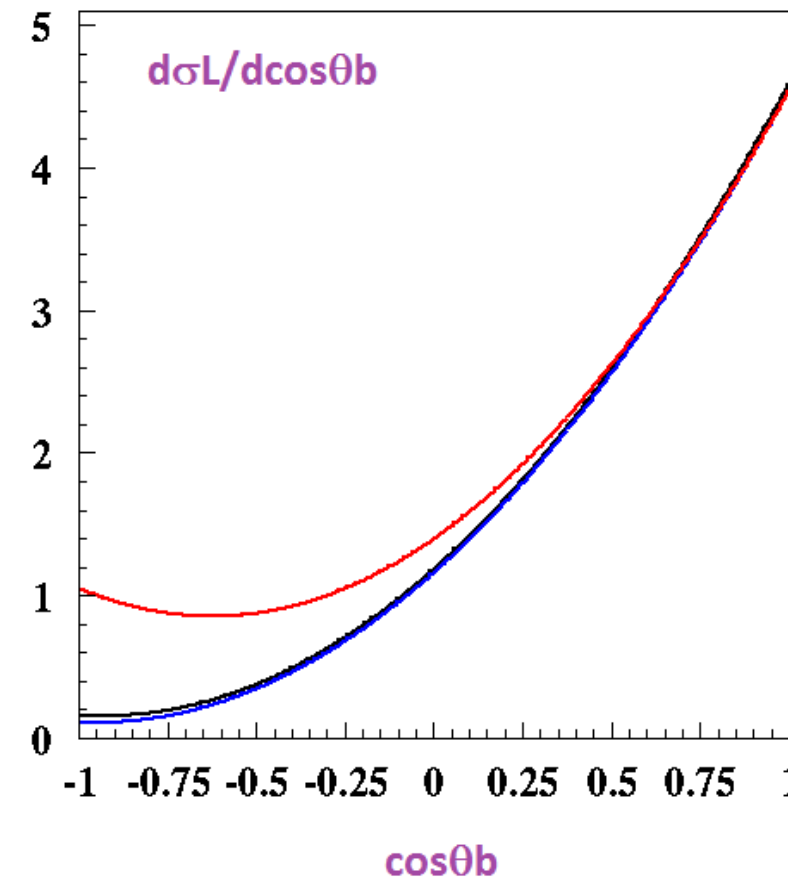
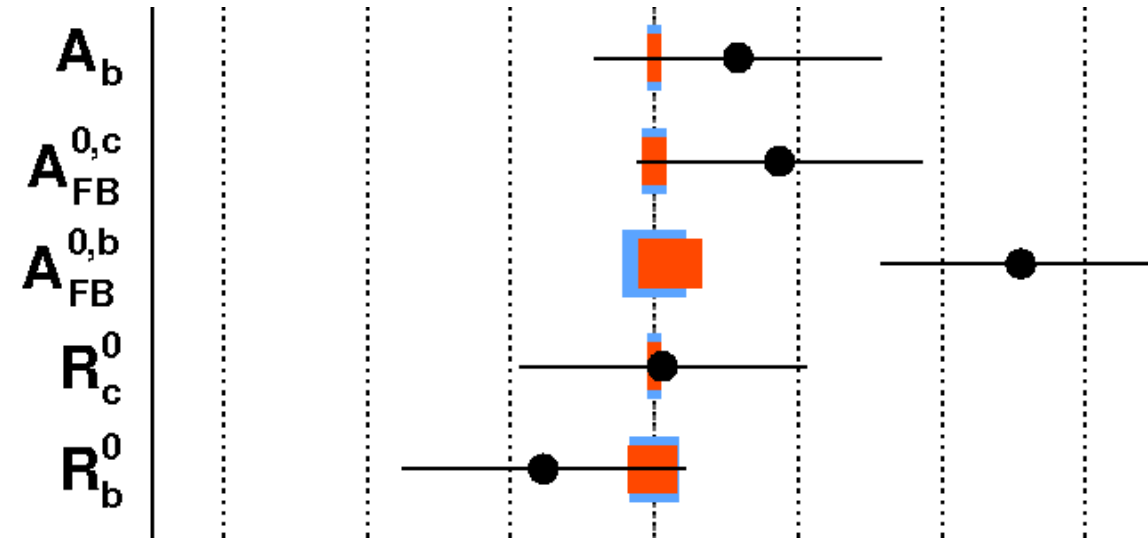


Extraction of relevant unknowns

$$\begin{array}{c}
 F_{1V}^\gamma, F_{1V}^Z, F_{1A}^\gamma = 0, F_{1A}^Z \\
 F_{2V}^\gamma, F_{2V}^Z
 \end{array}
 \quad \text{or equivalently} \quad
 g_L^\gamma, g_R^\gamma, g_L^Z, g_R^Z$$

$\sim 3\sigma$  in heavy quark observable  $A_{FB}^b$

ee- $\rightarrow$ bb@250 GeV



- Is tension due to underestimation of errors or due to new physics?

- High precision e+e- collider will give final word on anomaly

Randall Sundrum Models Djouadi/Richard '06

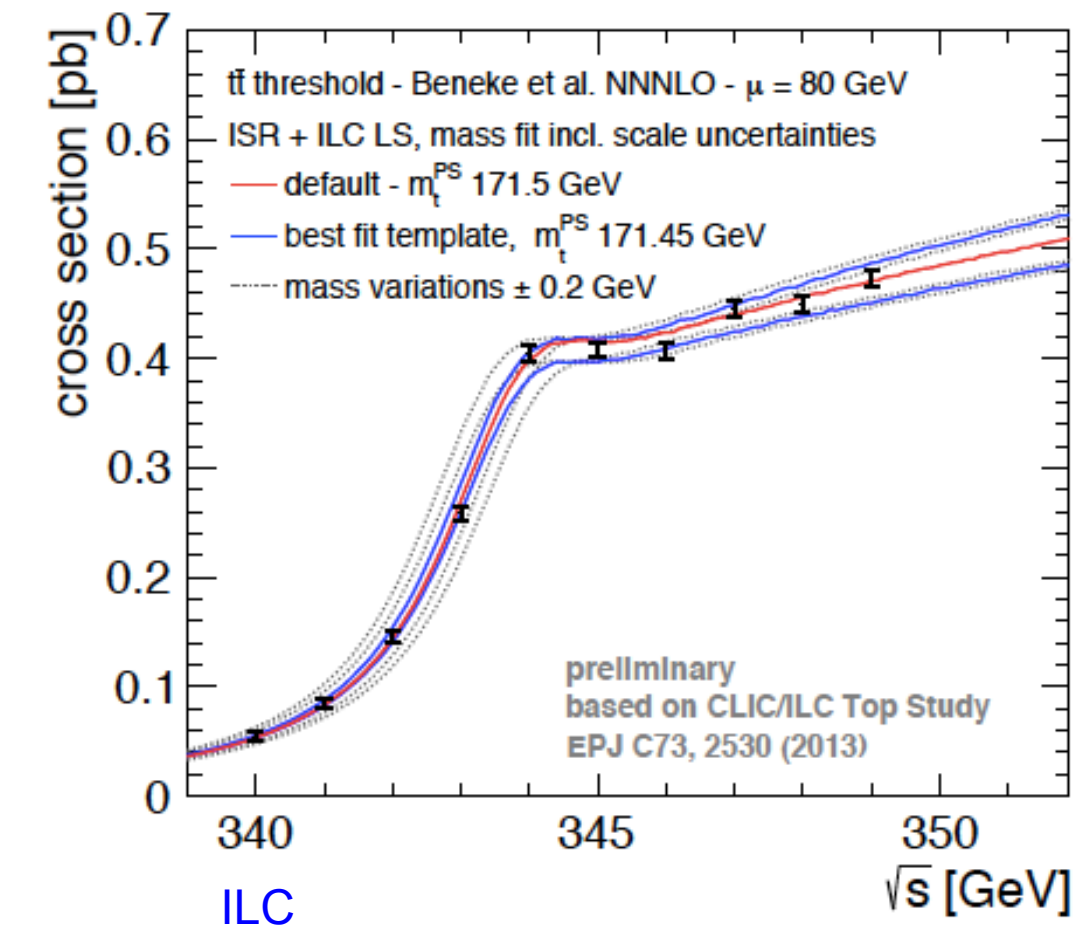
- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings (Remember  $Zb_l b_l$  is protected by cross section)

- Note that also B-Factories report on anomalies

EF Workshop Sept. 2021

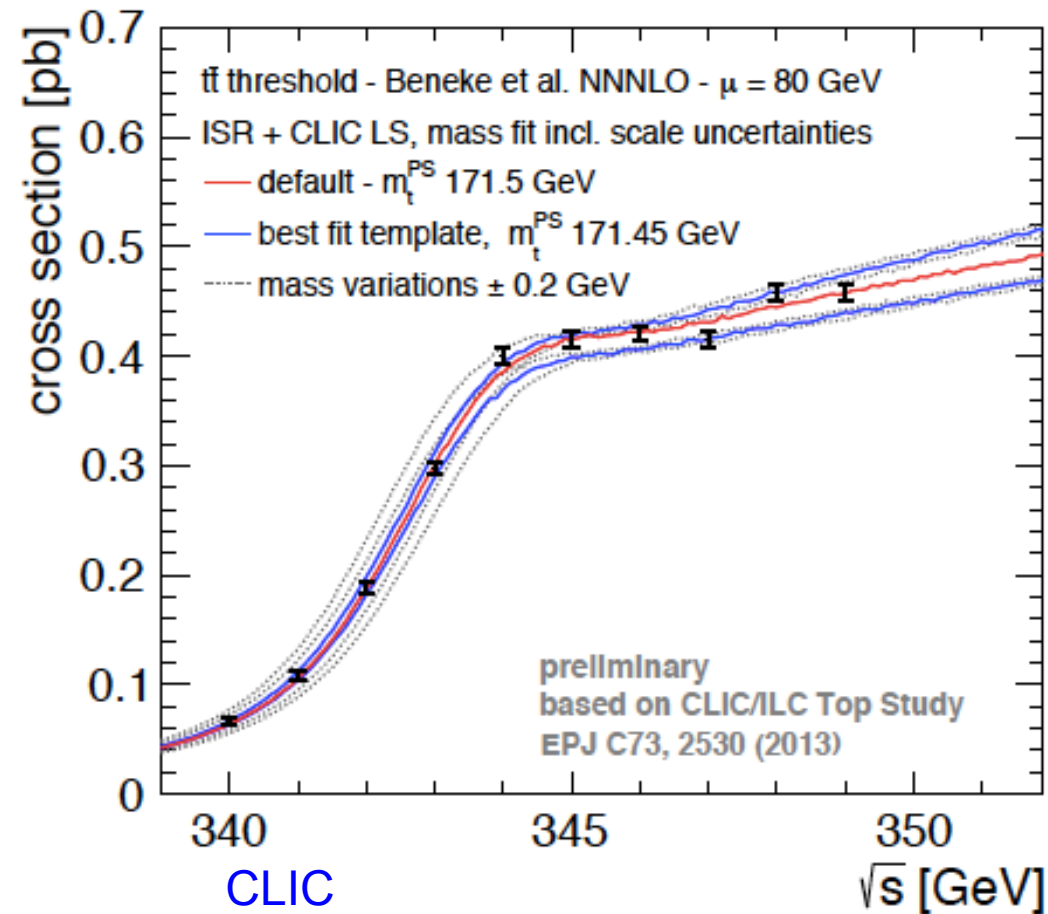


# Top pair production at threshold



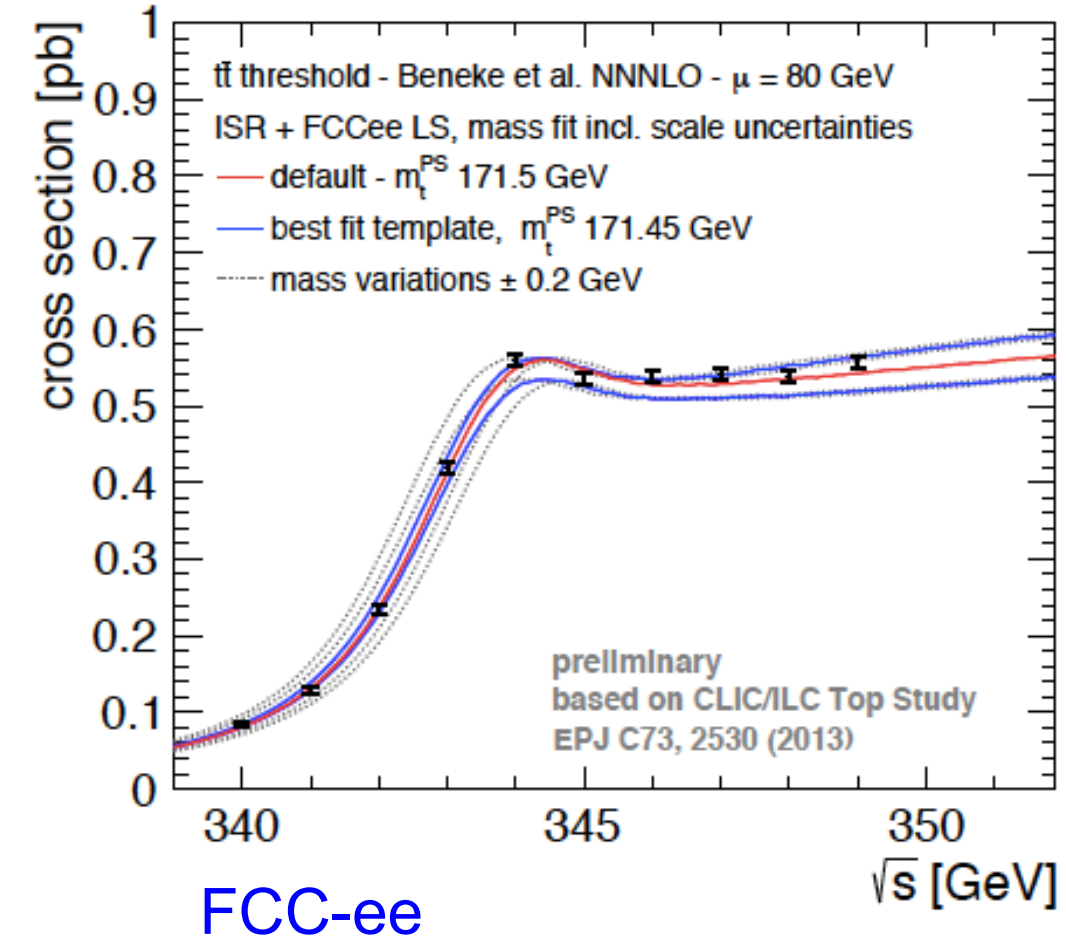
Fit uncertainty:  
28.5 MeV (18 MeV stat)

Scale uncertainty:  
40 MeV



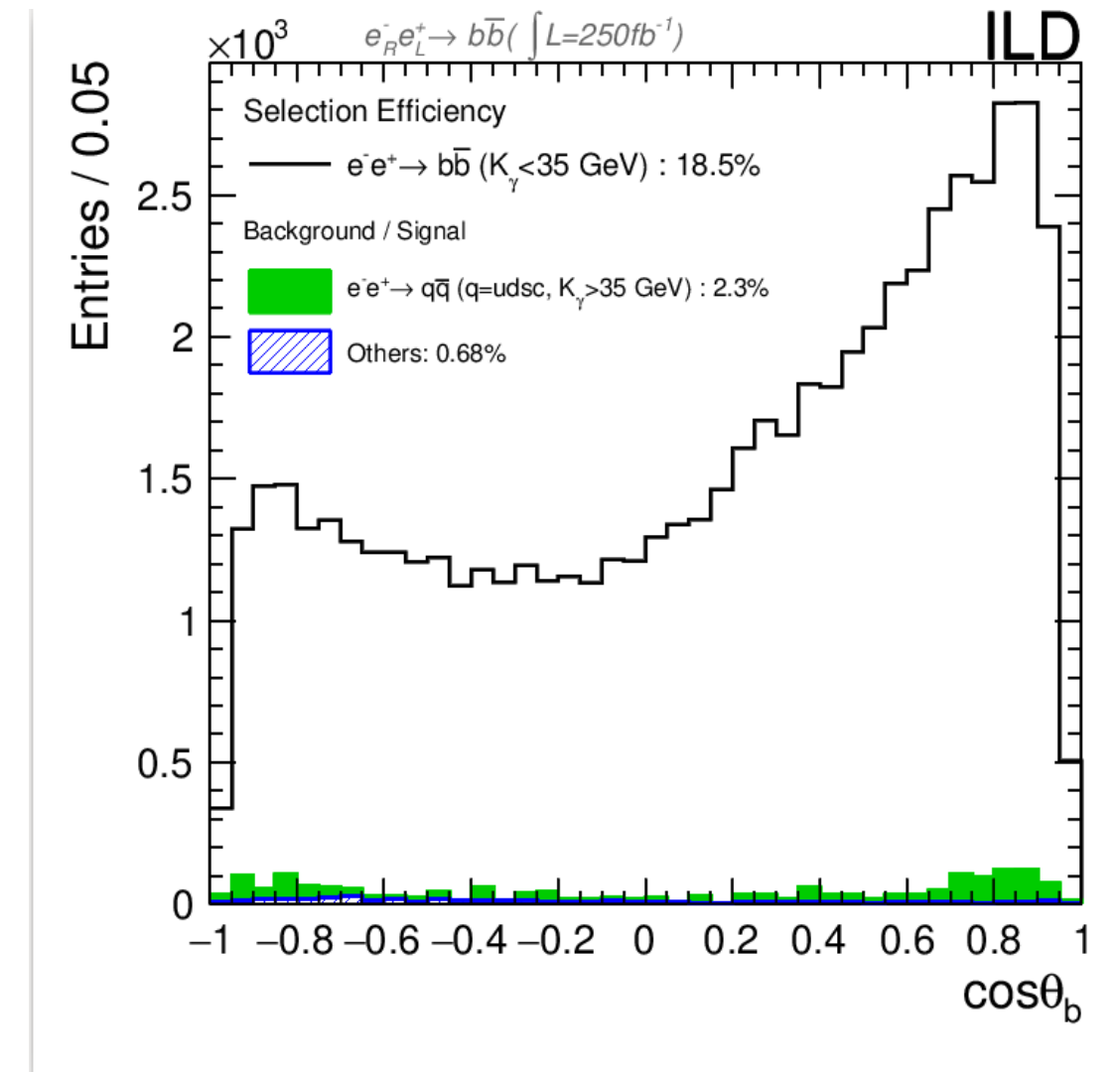
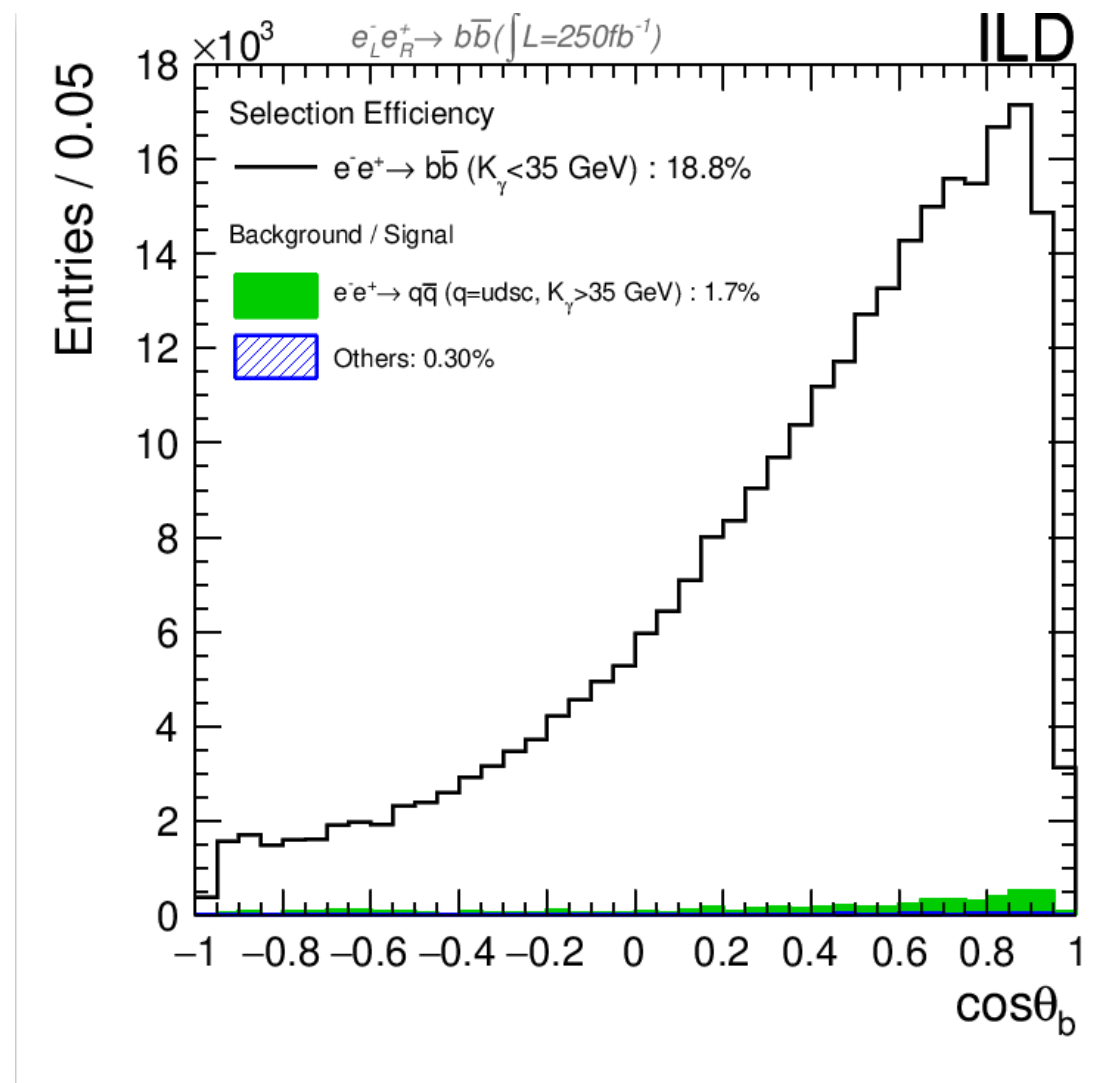
Fit uncertainty:  
31 MeV (21 MeV stat)

Scale uncertainty:  
42 MeV



Fit uncertainty:  
27 MeV (15 MeV stat)

Scale uncertainty:  
40 MeV



- Background levels can be kept at very small level
- However, these type of analyses seek per-mille level precision